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Review

Dissipation of ‘dark energy’ by cortex in knowledge retrieval

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Abstract

We have devised a thermodynamic model of cortical neurodynamics expressed at the classical level by neural networks and at the quantum level by dissipative quantum field theory. Our model is based on features in the spatial images of cortical activity newly revealed by high-density electrode arrays. We have incorporated the mechanism and necessity for so-called dark energy in knowledge retrieval. We have extended the model first using the Carnot cycle to define our measures for energy, entropy and temperature, and then using the Rankine cycle to incorporate criticality and phase transitions. We describe the dynamics of two interactive fields of neural activity that express knowledge, one at high and the other at low energy density, and the two operators that create and annihilate the fields. We postulate that the extremely high density of energy sequestered briefly in cortical activity patterns can account for the vividness, richness of associations, and emotional intensity of memories recalled by stimuli.

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Keywords: Carnot cycle; Criticality; Dissipative quantum model of brain; Ephapsis; Null spike; Phase cone

Contents

1. Introduction	2
1.1. Knowledge, information and energy	2
1.2. Modeling knowledge construction with the Carnot cycle	3
2. Macroscopic fields and many-body dynamics	4
3. Discussion and conclusion	7
Appendix A. Brain dark energy and the need for high energy density	8
Appendix B. Essential formal features of the dissipative many-body model	8
References	9

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1. Introduction

The aim of this review is to study the energy consumption of the brain in the framework of the dissipative many-body model [1–3] and the generalized Carnot cycle model [4]. We focus our attention on the expenditure of energy to facilitate the emergence of patterns and dissipation of so-called “dark energy” in knowledge retrieval. The general picture of the process by which brains construct knowledge from information and how the generalized Carnot cycle describes it is presented in the following subsections. In Section 2 we consider the interplay between the macroscopically observed high energy need of the brain and the many-body dynamics underlying the brain functional activity. Conclusions are presented in Section 3. In Appendix A the brain metabolic need of high energy density in conjunction with its dark energy dissipation is described. In Appendix B a brief summary of essential formal features of the dissipative many-body model is presented.

1.1. Knowledge, information and energy

Brains are thermodynamic systems that use chemical energy to construct knowledge from information [5,6]. The oxidative metabolism of glucose provides the energy, as measured by oxygen depletion and carbon dioxide production. The sensory receptors in the body and on the body surface provide the information by absorbing energy of various types impinging from the internal and external environments [7]. Each sensory receptor converts a stimulus, which is a local quantity of energy (light, heat, sound, concentration of a chemical), first to an ionic current (known as its receptor potential) and then to a train of pulses (action potentials, units, spikes) on its axon. Each pulse expresses a quantity of information by its location in time and space. The pulse train constitutes a point process. The sensory energy is weak [8], often a few molecules of scent, a few photons in a flash. Detection is facilitated by large arrays of equivalent receptors (10^7 – 10^8). The arrays form sheets on the body surfaces, which send bundles of axons into the brain. A stimulus is a configuration of energy in a pattern that is transmitted as information by the pulse intervals, frequencies and delivery sites by stages to the sensory cortices. A conditioned stimulus is a stimulus that has been paired with a painful or pleasurable unconditioned stimulus in reinforcement learning. It is in sensory cortex that the sensory information is organized at high density as knowledge and accumulated over the lifetime of an individual as memories.

In an act of recognition a conditioned stimulus triggers an operator, a Hebbian nerve cell assembly, that abstracts, amplifies and generalizes to the category of a stimulus [9]. The assembly forms by repeated samples of information in reinforcement learning according to the Hebb rule: neurons that fire together wire together. The conditioned stimulus ignites the entire assembly, so the output signals the category of the stimulus and not the stimulus *per se*. The associations learned under reinforcement convert the input of sensory information to the output of a fragment of knowledge. The assembly provides the bolus of energy required to generate a structured liquid-like phase (low entropy) out of a formless gas-like phase of random activity (high entropy), with a vanishing change in the free energy F , $dF = 0$. Such a process of phase transition is by spontaneous breaking of the symmetry of the gas-like phase [3], in the sense that the pre-stimulus phase is featureless in all directions, whereas the pattern of the post-stimulus phase cannot be rotated or translated into itself.

The conditioned stimulus ignites the entire assembly, so the output signals the category of the stimulus and not the stimulus *per se*. The assembly provides the bolus of energy required to initiate a phase transition from a formless gas-like phase of random activity to a structured liquid-like phase. The phase transition is by spontaneous breaking of the symmetry of the random phase [3].

The fragment of knowledge consists of the (low entropy) ordered pattern generated from broken symmetry. It is expressed in two interactive fields of neural activity, which spread over the entire sensory cortex. The dendrites of the neurons generate a high-energy-density field of electric current that synchronizes cortical activity in a narrow-band oscillation. The knowledge content is expressed in the spatial pattern of amplitude modulation (AM) [7,9,10]. In the biological model these AM patterns are generated by attractors that are structured by modified synapses constituting memories formed by learning in consolidation. The spread over the cortex is documented by a spatial pattern of the phase defined at the carrier frequency. The phase pattern has the form of a cone [10]; the phase gradient and velocity are determined by the carrier frequency and the conduction velocities of intracortical axons; the location and sign of the apex (phase lead or lag) vary randomly from each wave packet to the next regardless of contents. The inward phase

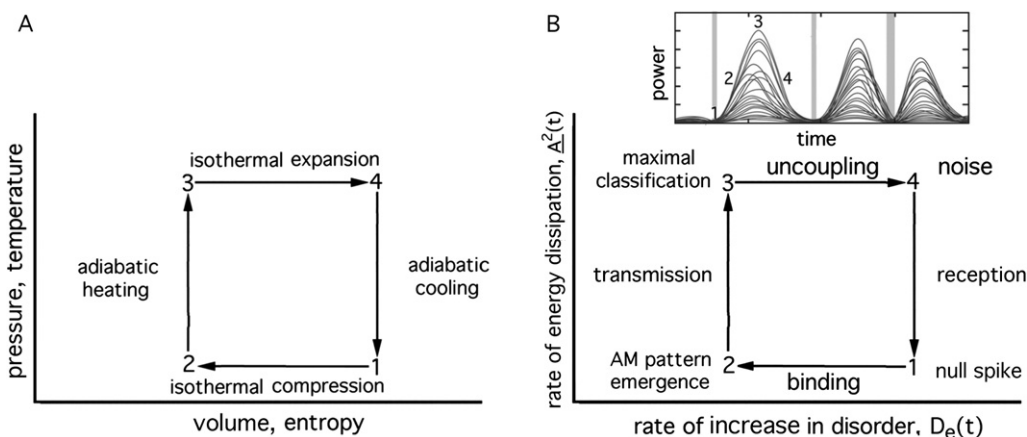


Fig. 1. (A) An ideal Carnot cycle is illustrated with four isoclines for a heat engine. (B) The upper inset illustrates a sequence of three Carnot cycles carrying AM patterns in the superimposed filtered ECoGs from 64 electrodes. The variables representing temperature and entropy are replaced with indices derived from multichannel EEG recording. We start the cycle (1) at minimal mean power, $\bar{A}^2(t)$, and maximal chaotic disorder, $D_e(t)$. At the other extreme (3) the power and information are maximal (the disorder is minimal). The knowledge increment is estimated from the area in the rectangle, which defines the pragmatic information [15]. From Freeman and Quiroga [6].

gradient to maximum lag at the apex indicates that the AM pattern and phase cone are fixed at burst onset before they unfold.

In the dissipative many-body model, the attractors (and the AM patterns) are represented by the ordered ground states towards which the system naturally evolves (is “attracted”). Ordering is generated by the long range neuronal correlation sustained at quantum level by the electric dipole quanta A of the water matrix in which neurons and glia cells are embedded. These quanta are the so-called Nambu–Goldstone (NG) quanta whose existence is required by the NG theorem in the hypothesis that spontaneous symmetry breakdown occurs; they are the quanta carrying the ordering information through the system volume; for an extended discussion on this point see [1–3,12].

The axons generate a low-energy-density pulse cloud, a field of action potentials, which mediates the interactions among the dendrites in circular causality, thus reading out the high-energy-density field of electric current synchronizing the cortical activity. Axonal pulse clouds find their counterpart at quantum level in the field of \tilde{A} quanta duplicating the quanta A since they are coupled with dendritic current fields always in pairs. These axonal pulse clouds (and the \tilde{A} quanta in terms of which they are described) are crucial in balancing the high-energy-density field of electric current thus avoiding, from one side, exploding run-away activity and, from the other side, synchronizing the cortical activity. This is why the A and the \tilde{A} quanta occur always in pairs. We thus have the double set of quantum modes A and \tilde{A} and a continuously balanced exchange of energy flows between the two sets. The synchronization of the cortical activity and its *in phase* occurrence with the pulse cloud field are the manifestation of the many-body coherence of the A – \tilde{A} condensate (see Section 2 and Appendix B). The pulse cloud is down-sampled [6] to transmit cortical output needed for the central integration, which thus appears as the overall result of the many-body coherence. The oscillation is terminated (dissipates) after 3–5 cycles by an operator based in the bandwidth of the carrier frequency, thus requiring to incorporate dissipation [1] in the many-body model of brain [13]. This operator has been modeled using Rician statistics of extreme values [9] (see [14]). We stress that in the dissipative many-body model, neurons, EEG potential fields, pulse clouds, glia cells, dendrites, axons and other biological units are classical objects; the quantum variables are the ones associated to the quanta, A and \tilde{A} , of the electric dipole field of the water molecules and other molecules.

1.2. Modeling knowledge construction with the Carnot cycle

The thermodynamic process of creating knowledge from information in a sensory cortex is cyclic. We have modeled the process using the generalized Carnot cycle [4], in which entropy is reduced by the expenditure of energy to facilitate the emergence of patterns (Fig. 1). We have observed the patterns in trained animals by using arrays of electrodes to record the electroencephalogram (EEG, technically the electrocorticogram, ECoG, from the surfaces of the visual, auditory, somatic and olfactory cortices) as the animals respond to conditioned stimuli [11].

Each cycle has four steps. A cycle begins with a sensory cortex in a basal state of random background activity with low analytic power, $A^2(t)$, that is symmetric in having $1/f$ power spectral density (PSD) and no spatial or temporal pattern. The arrival of a stimulus-evoked sensory volley of pulses breaks the symmetry by initiating a narrow band oscillation that synchronizes the background pulse firings without increasing mean rates (isothermal compression), which causes a peak on the PSD and creates a spatial pattern of amplitude modulation (AM) in the EEG. We measured the AM patterns and deduced from the space–time changes the rate of entropy production, $D_e(t)$ (also information increase, $1/D_e(t)$). Each digitizing step increases the certainty of the AM pattern, hence adding increments of information.

In step two the AM pattern is fixed, and the analytic power continues to rise, not by synchronization but by expenditure of energy in transmission of the AM pattern (adiabatic heating), leading to maximal power and minimal entropy, with maximal classification of EEG patterns with respect to the conditioned stimuli containing information.

In step three the AM pattern dissolves as the firing rates diminish owing to the refractory periods of the neurons, and the strength of synaptic coupling wanes (isothermal expansion). In step three the AM pattern dissolves as the firing rates diminish owing to the refractory periods of the neurons, and the strength of synaptic coupling waves (isothermal expansion). In step four the synchronization is annihilated as the distribution of characteristic frequencies in the PSD spectral peak go out of phase and cancel (adiabatic cooling). We define the area enclosed by the loop as a measure of pragmatic information [15], which is the ratio of the rate of energy dissipation (power) to the rate of decrease in entropy (increase in information).

The transition from step four to step one requires not only the emergence of a new AM pattern but the rapid and reliable extinction of the commitment of energy to an attractor. Our experimental data suggest that a singularity [5,9] is involved that appears during the temporal minima of analytic power. Cinematic display of $\log_{10} A^2(t)$ reveals brief, sharply localized minima denoted as null spikes (Fig. 2B), at which the power may decrease from the mean levels by 6 orders of magnitude or more, coinciding with a temporal discontinuity in the analytic phase, and perhaps with the apex of phase cones and the centers of rotation of vortices [6,16], though these relations have not been proven experimentally.

2. Macroscopic fields and many-body dynamics

The activated knowledge in each cycle consists of the concomitant and coincident fields of activity, the high-energy-density field of dendritic currents (sustained at the quantum level by the A quanta) and the low-energy-density cloud of axonal pulses (sustained at the quantum level by the \bar{A} quanta), respectively. Both are synchronized (A – \bar{A} coherence) in the same narrow band carrier frequency of the wave packet. The contents of the activated knowledge in each sensory cortex are observed and measured in the spatial AM pattern of the EEG manifesting the dendritic current density, which controls the intervals between pulses and thereby determines a pattern of pulse density in the cloud. The pulse cloud determines the current densities in circular causality, and it down-samples and transmits the information content of the AM pattern. Owing to sampling limitations the pattern in the cloud cannot be measured directly, so the conceptual contents are inferred from the macroscopic dendritic potentials [17] and confirmed through ensemble averages of pulse trains from selected neurons [18–20].

We infer that the dendritic AM pattern is transmitted by the pulse cloud covering the whole of each sensory cortex. The memory bank and the sensory information exist at a microscopic level of single neurons and synapses, comparable to atoms and molecules and their attachment sites. The active memory is a macroscopic collective field of energy that is sustained by the interactions of millions of neurons and billions of synapses. We postulate that the background activity prior to a stimulus trigger is sparse, random firing of neurons in low-density comparable to a gas-like phase, and that the recollection of a memory fragment forms by a phase transition of the cortex as it condenses to a patterned liquid-like phase. Macroscopic signals are transmitted by time multiplexing of seemingly random pulse trains in each local neighborhood [6]. After transmission of the wave packet the activity evaporates (dissipates), and the cortex irretrievably annihilates the initiating information and its context.

The cycle is exceedingly energy-intensive, almost equally in the two alternating phases of reception and transmission. The metabolic processes involved in the energy collection and consumption are described in Appendix A. In the following we focus our attention on the energy requirements for criticality and phase transitions. Indeed, a further de-

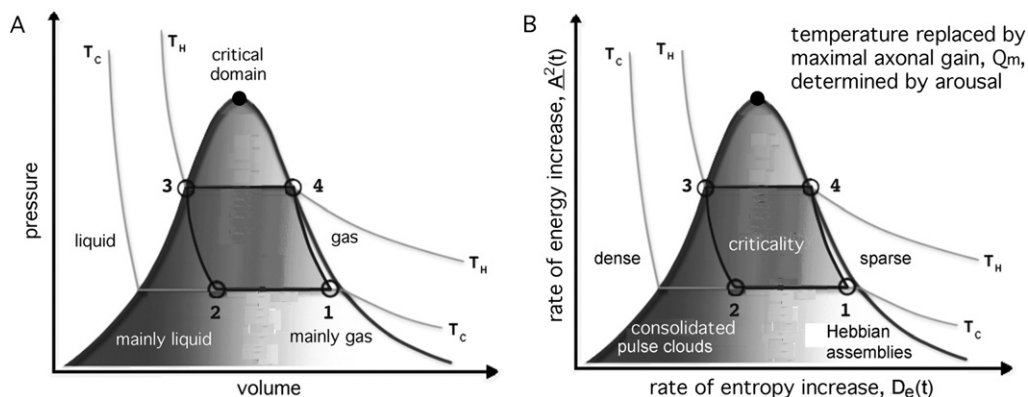


Fig. 2. (A) The four steps that comprise the generalized Carnot cycle are shown in a domain of criticality maintained by neural avalanches (see Section 6.9 in Freeman and Quian Quiroga [6]). The gas and liquid phases coexist in varying degrees. In this formulation energy is put in by heating in (2–3) and removed as waste heat in cooling (4–1). (B) We conceive the operation of cortex as using information from step (1) to select, construct, and transmit knowledge in step (3). The height of the cycle (2–3) is determined by the degree of arousal as indexed by the asymptotic maximum of axonal gain, Q_m [27]. Average brain temperature is homeostatically regulated by blood circulation, but local fluctuations, T , are widespread and closely related to analytic power. Free energy is derived from oxidative metabolism and is dissipated as heat in all four steps. Adapted from [28] in Freeman and Quian Quiroga [6].

mand for energy is imposed by the requirement for background activity in resting neuropil¹ in living brains. The steady state random activity is governed by a non-convergent ‘chaotic’ attractor, which is sustained by the positive feedback by which the excitatory neurons continually excite each other, restrained from excessive firing by their refractory periods [21]. The mutual excitation maintains a steady state of criticality [6] far from thermodynamic equilibrium (Fig. 2), expressed by neural avalanches.² Criticality sustains a high-energy state of readiness for phase transition to meet the exigencies of an unpredictable and dangerous world, which adds to the losses of energy by leakage, thus constantly dissipating energy in self-sustained clouds of axonal action potentials and dendritic currents. The many-body dissipative model allows us to compute the condensate energy supplying the energy requirements for criticality and phase transitions. Thus we present such a computation in the following.

Essential aspects of the formalism of the dissipative model are very briefly summarized in Appendix B (details can be found in [1,3]). In the notation there introduced, $|0\rangle$ and $|0(\theta)\rangle_N$ denote states of the brain activity corresponding to the absence of quanta A_k and \tilde{A}_k (the vacuum $|0\rangle$) and the condensate state of condensation density N_{A_k} (and $N_{\tilde{A}_k}$), respectively.

We observe that for the inner products (the overlaps) of these states the relations hold: $\lim_{V \rightarrow \infty} \langle 0|0(\theta)\rangle_N = 0$ and $\lim_{V \rightarrow \infty} N \langle 0(\theta)|0(\theta)\rangle_{N'} = 0$, for any N and any $N' \neq N$. These relations signal that in the limit of infinitely many degrees of freedom (the infinite volume limit of quantum field theory) the process of condensation of the A and \tilde{A} modes is a phase transition process: the states $|0\rangle$ and $|0(\theta)\rangle_N$, for any N , represent ‘distinct’ phases in the brain activity since no overlap exist among them for different values of N . These relations also express the criticality present in the brain background activity since their meaning is that no unitary transformation exists able to lead from one phase coded by N to another phase coded by N' , with $N' \neq N$: they are ‘unitarily inequivalent phases’ and transitions from phase to phase are critical transition processes. The criticality here identified is characterized by chaotic, scale-free behavior and power laws, as indeed laboratory observations show [18,29], which are features

¹ The noun ‘neuropil’ denotes an exceedingly dense network of interwoven glial filaments, unmyelinated nerve axons, dendrites, and their branches and synapses, together with the supporting cell bodies and capillaries supplying nutrients and removing waste products. Neuropil extends throughout the brain and spinal cord, embedding the nuclear masses. Reticular neuropil occupies the core of the brain stem and spinal cord. Laminated (layered) neuropil forms the cerebral cortex, the colliculi in the midbrain, and outer parts of the spinal cord as the substantia gelatinosa, where its properties have been analyzed in greatest detail [22,23].

² The phrase ‘neural avalanches’ denotes the occurrence in resting neuropil of myriad brief bursts of pulse firing and dendritic oscillations in analogy to the model of self-organized criticality [21,24–26], in which a sand pile with steady input maintains a critical angle by avalanches having power-law distributions of amplitude, duration and interval. The model suffices to simulate the maintenance of a steady state level of neural background activity in the face of continuous bombardment by input, but it does not support modeling of the phase transitions we observe in cortical electrical activity [4].

implied by the model since phase transition processes turn out to be described by chaotic “trajectories” from phase to phase [30], and coherent states such as $|0(\theta)\rangle_N$ have been shown to be characterized by scale-free, power law features [31–33].

Next, the condensate density in the state $|0(\theta, t)\rangle_N$, the time evolved at time t of $|0(\theta)\rangle_N$, is given by [1]

$$N_{A_k}(t) = {}_N\langle 0(\theta, t) | A_k^\dagger A_k | 0(\theta, t) \rangle_N = \sinh^2(\Gamma_k t + \theta_k) = \frac{1}{e^{\beta(t)E_k} - 1}, \quad (1)$$

where Γ_k denotes the life-time constant of the k -mode A_k (the NG quantum of momentum k) and $\beta(t)$ is assumed to be slowly varying in time in order to ensure that quasi-stationary conditions be satisfied at any time t . We finally compute the energy contribution of the (vacuum) condensation density (1) (the brain ‘dark energy’) to the energy requirements for criticality and phase transitions. In a standard fashion, the energy density of the condensate, at a given time t , is given by

$$\rho = \int d^3k \omega_k {}_N\langle 0(\theta, t) | : A_k^\dagger A_k : | 0(\theta, t) \rangle_N \quad (2)$$

where $: \dots :$ denotes the normal ordering with respect to the vacuum $|0\rangle$. Then

$$\rho = 4\pi^2 \int_0^\infty dk k^2 \omega_k \sinh^2(\Gamma_k t + \theta_k) = 4\pi^2 \int_0^\infty dk k^2 \frac{\omega_k}{e^{\beta(t)E_k} - 1}. \quad (3)$$

Setting the phase velocity $v_p = 1$ and $\hbar = c = k_B = 1$, for massless fields, such as NG fields, $\omega_k = k$, the above integral becomes

$$\rho_{m=0} = 4\pi^2 \int_0^\infty dk \frac{k^3}{e^{\beta(t)E_k} - 1} = \frac{4}{15} \pi^6 T^4(t). \quad (4)$$

Boundary effects and impurities, however, may contribute to give a non-vanishing effective mass to the NG fields [12,16]. In such a case of massive fields, the integral in Eq. (3) can be solved numerically. It converges and its upper bound is given by Eq. (4).

From the minimization of the free energy F_A of the A quanta, $dF_A = dE_A - (1/\beta) dS_A = 0$ one recognizes that $E_A \equiv \int d^3k \omega_k N_{A_k}$ is the internal energy of the system. S_A is the entropy and as usual heat is $dQ = dS_A/\beta$. Thus the change in time of condensate, dN_{A_k}/dt , turns out into heat dissipation dQ . $dF_A = 0$ expresses the first principle of thermodynamics for a system coupled with environment at constant temperature and in absence of mechanical work. The non-equilibrium dynamics has been studied in detail by use of the Ginzburg–Landau (GL) time dependent equation in Freeman, Livi, Obinata and Vitiello [34]. It happens that for any $t \neq t'$ it is $\lim_{V \rightarrow \infty} {}_N\langle 0(\theta, t) | 0(\theta, t') \rangle_N = 0$, which shows that brain activity is far from the equilibrium and characterized by criticality at any time t . Time evolution of the phase coded by same N appears to be a far from the equilibrium critical process ($|0(\theta, t)\rangle_N$ and $|0(\theta, t')\rangle_N$ are unitarily inequivalent phases). In the case of non-stationary regime, one is interested in the non-vanishing dF expressing the rate at which the system approaches the stationary regime at the minimum of the free energy. In [34] the time-dependent GL equation is obtained and it is shown that the rate of change of the condensate dN_A/dt in the non-stationary regime, named the critical GL regime, is proportional to the relaxation term $\mathcal{R}_{diss} \equiv -\Gamma_R N_A$, with the ‘damping’ $\Gamma_R \equiv \Gamma_1 + \Gamma_2$, where Γ_1 depends on the diffusion coefficient $D_{GL} \equiv \xi_{GL}^2/\tau_{GL}$ (ξ_{GL} and τ_{GL} are the GL correlation length and the GL relaxation life-time, respectively). Γ_2 depends on non-homogeneities. The picture one obtains [34] is the one of the non-stationary hydrodynamics (liquid-like regime, indeed). In the brain activity, the brain is continuously moved out from its ground state activity entering a non-stationary dynamical regime. During such a non-equilibrium phase transition process, the system dynamics turns out to be characterized by topologically non-trivial structures (vortices), which are described by non-homogeneous boson condensation processes. The size, life-time and number of these topological structures appearing in the phase transition process have been estimated and discussed [34].

In conclusion, from our results and from hemodynamic studies it appears that brains store an immense amount of energy in the transmembrane ionic gradients of Na^+ , K^+ and other ions, which are replenished by metabolic activity at more leisurely background rates. The reservoir meets the energy requirements for criticality and phase transitions

and may be considered to provide immediate access to energy for the exchanges in the Carnot-like cycle discussed above.

3. Discussion and conclusion

The property of brains we address in this review is the complexity of associations that we experience in flashes of recognition in recall induced by sensory stimuli. Three outstanding structural features of the neuropil explain the richness of detail. One is the high divergence and convergence among axons and dendrites in neuropil [36], with power-law distributions of connection distances that facilitate scale-free neurodynamics [28]; another is the extreme packing density of cells and fibers, which brings enormous numbers of neurons and synapses within the correlation range for synchronization of neuronal activity; a third is the maintenance of the neuropil in a state of criticality [20], a readiness for abrupt change by phase transitions from expectancy to realization and back again repeatedly in tracking changes in the environment [6].

These features can readily explain the observations of the ‘dark energy’ at high density and rate of dissipation by neuropil, which have their greatest values in the human brain at the pinnacle of biological intelligence. What is to be modeled and explained is the mobilization of the myriad microscopic details that are stored in the modified synapses among the interconnected neurons into the macroscopic order that is expressed by the pulse cloud and its controlling field of dendritic currents, which we observe in the EEG and experience in flashes of insight.

What is unclear is the extent to which the active states established in excitatory and inhibitory neurons spread into the tips of active dendrites. On the one hand, the fine tips may only provide additional surface area to the dendritic trees for new synapses on excitatory and inhibitory neurons by supporting the growth of the dendritic trees for new synapses but with no direct contributions to interactions. On the other hand, they may interact by ephapsis³ to the ionic currents from their neighbors densely packed in the neuropil. Ephaptic transmission has been thoroughly documented to occur in the *substantia gelatinosa*, a form of laminated neuropil that resembles cortex in the sensory gray matter of the spinal cord [22,37]. It occurs only with states of intense excitation or extreme sensitivity, such as in pain [23], so it is generally regarded as pathological. It has also been reported to mediate remarkable increases in synchronization of neural firing *in vivo* in cortical slices [38].

Our data from EEG recording suggest that ephapsis may play a role in the phase transition by which the low-density background activity rapidly changes to high-density activity with synchronization with emergence of an AM pattern, provided that the cortex is in criticality, and that there is a source of a bolus of transition energy. Our thermodynamic model is based on a generalization of the Carnot cycle, the Rankine cycle (Fig. 2), which is embedded in a critical domain, such that with increasing density of interactions the neural activity condenses into the liquid-like phase, and it evaporates by uncoupling into the gas-like phase. In the dissipative many-body modeling of brain, we argue that the condensation requires an operator that creates the AM pattern by sequestering a large quantity of energy in the high-density state, and that the energy is relinquished as heat on return to the basal state through annihilation of the AM pattern by a second operator. It is these operators that bring microscopic information stored in memory into macroscopic knowledge on-line and then expunge it immediately after down-sampling to the microscopic level for transmission.

What role does ephapsis play in sustaining a wave packet? There is a threshold of energy density for induction of ephaptic transmission by direct electrical interaction among all fiber terminals, which promotes synchronization of firing of neurons in neuropil [38]. Dendritic current fields are coupled with axonal pulse clouds always in pairs. We postulate that interaction by ephapsis qualitatively distinguishes the liquid-like phase from the gas-like phase, because it increases the density of interaction to include the maximum of information retrieval under the guidance of axodendritic synaptic transmission in the shaping of AM patterns occupying very large areas of cortex. No one knows exactly how ephaptic transmission works, because the packing density is too great to allow use of existing electrophysiological methods. Candidate mechanisms may include coupling through water dipoles [16], because both the intracellular and extracellular compartments are weak ionic solutions comprising more than 80% water with high electrical conductivity on either side of the lipid bilayers. The condensate of dipole wave quanta A and \bar{A} may indeed provide the proper dynamical environment and the necessary energy to promote direct, non-synaptic, point coupling

³ Ephapsis from the Greek word for ‘touch’ denotes action of a neuron on others in apposition that is mediated by local chemical and/or electrical fields and not by chemical or electrical synapses [35].

between neighboring axons and dendrites. Ephaptic coupling and transmission among fiber terminals may then result to be another macroscopic manifestation of the many-body dynamics. The computation of the energy contribution coming from the brain background activity state presented in the present review may represent a step forward in the understanding of the ephaptic coupling.

Appendix A. Brain dark energy and the need for high energy density

In comparison to other tissues the human brain has 2% of body mass but dissipates 20–25% of resting energy (2–8% in most vertebrates, 10–15% in lesser primates), as measured by oxygen depletion in the venous return from the brain, compared with total body consumption of oxygen. Imaging of blood oxygen levels of depletion (BOLD) with O^{15} and positron emission tomography (PET) in various regions has shown that the neurons in cerebral cortex are most demanding [36], followed in descending order by those in basal ganglia, brain stem and white matter [39–41], which have rates comparable to those for heart, liver and kidney, still above the resting rates for most tissues of the body. The ten-fold discrepancy for human cortex above the whole body has led to the sobriquet ‘dark energy’, in analogy to dark matter in astrophysics [42].

The high energy density and dissipation are imposed by the immense connectivity among neurons that is required to interconnect manifold information into knowledge at high density. What most distinguishes neurons from other cells is their unique shape. The long axonal filaments with multiple branches provide the basis for the strong divergence from each neuron to $\sim 10^4$ other neurons [43]. The radiating dendritic trees provide the immense surface area required for the converging synapses from roughly 10^4 other neurons, each of which must have a current path to the trigger zone. The density of cells is exceedingly high: $10^5/\text{mm}^3$. The embedding glial cells outnumber the neurons 10 : 1 in humans and contribute their filaments to the neuropil. The cell bodies of most cortical neurons are aligned in layers, and the dendrites and axons tend to be oriented parallel or perpendicular to the cortical surface, often in bundles [44]. The cortex is a thin layer, in humans 2–4 mm in depth and $2\text{--}3 \times 10^5$ mm in area. The resulting small volume compared to the large area drives the wrinkling of the cortical surface into the gyri and sulci. A network of capillaries provides nutrients and O_2 and removes CO_2 ; it also provides a low resistance extracellular path for dendritic currents. The dense mix of filaments in cortical tissue resembles the pile of a rug; hence the anatomical term: ‘laminated neuropil’.

The fineness of compartmentalization of the neuropil by neural membranes of the fibers far exceeds that of any other tissue. Most filaments are so small that they can only be seen by electron microscopy; the minimum diameter is 0.1 μm ; the median diameter in cross-section being 0.11–0.2 μm [45]. To receive and transmit information each fiber maintains the transmembrane gradients of Na^+ and K^+ required for the resting membrane potential by ionic pumps that are fueled by ATP from mitochondria. The rate of passive leakage of Na^+ and K^+ ions is proportional to the surface areas of the external membranes encasing the neurons and of passive H^+ ions due to the gradients across the internal membranes of the mitochondria. Hence the ultrastructure of cortex required for dense connectivity imposes intensive dissipation of chemical energy by brains both at rest and engaged in cognition.

According to the membrane pacemaker theory of metabolism [46], the differences in metabolism between cerebral and non-cerebral tissues are caused by differences both in membrane chemical composition and in ionic pumps. The polyunsaturated fatty acids that are characteristic of neuronal membranes have distinctive physical properties of flexibility that cause the proteins in the membranes such as the voltage-dependent ionic channels to have high molecular activity [47], which results in higher rates of metabolism. The long axons impose communication by Na^+ action potentials, so that only in neuropil (and to a lesser extent in kidney) does Na^+/K^+ -ATPase dominate energy production from glucose [36,48], constituting 40–47% of brain basal metabolic rate. Only neuropil has the supportive glial cells maintaining the blood–brain barrier, which sustains the necessary constancy of the fluid environment surrounding neurons by myriad biochemical reactions that cost energy, which cannot be estimated reliably, so inseparable are neurons and glia in normal function [49]. Only neurons sum excitatory and inhibitory synaptic potentials with subtraction to near-zero voltage, but with addition of the costs in metabolic energy.

Appendix B. Essential formal features of the dissipative many-body model

A full account of the dissipative many-body model of brain and its formalism is presented in [1–3]. Here we only present some formal features finalized to a better understanding of some remarks in the main text and in order to introduce notations there used.

As mentioned in Section 1.1, the NG quanta A_k and their condensation in the ground state are dynamically generated through the spontaneous breakdown of the symmetry triggered by the external stimuli. The NG theorem predicts that the NG quanta or modes have zero mass and thus they can span the whole system volume without inertia. Moreover, in the quantum formalism, to each quantum or particle one may associate a corresponding wave, and vice-versa. So, we may think of the A_k 's as the quanta of the (electric) dipole wave spanning the whole system. The NG quanta thus appear as collective modes since they express the collective dynamical interaction among the system quantum constituents in the regime of symmetry breakdown. Again, we stress that in the dissipative many-body model the quantum constituents are the electric dipole field quanta associated to the quantum fluctuations of the electric dipole field of water molecules and other molecule in the system. Neurons, glia cells, dendrites, axons and other biological units are classical objects.

By considering also the mirror quanta \tilde{A}_k (cf. Section 1.1), let $|0\rangle$ denote the state without A_k and \tilde{A}_k quanta (the vacuum state for the A_k and \tilde{A}_k quanta), namely the state which is annihilated by A_k and \tilde{A}_k , $A_k|0\rangle = \tilde{A}_k|0\rangle = 0$, for any k , $|0\rangle \equiv |N_{A_k} = 0, N_{\tilde{A}_k} = 0\rangle$, with N_{A_k} and $N_{\tilde{A}_k}$ denoting the number of A_k and \tilde{A}_k , respectively. We use for simplicity only one index k specifying the quantum numbers, e.g. the momentum, of the A and \tilde{A} operators.

The dynamical generation and the condensation of the NG modes, say at time $t_0 = 0$, leads to the new state $|0(\theta)\rangle_N \equiv |N_{A_k} = N_{\tilde{A}_k} \neq 0; \forall k\rangle$, with $N \equiv \{N_{A_k} = N_{\tilde{A}_k} \neq 0, \forall k, \text{ at } t_0 = 0\}$.

Note that equal numbers (couples) of A_k and \tilde{A}_k , for any k , are condensed in $|0(\theta)\rangle_N$. Since the NG modes (and their mirror modes \tilde{A}) are massless, the condensation of a number of them with vanishing momentum in the system ground state does not add energy to such a state. Thus, (infinitely) many condensed θ -states $|0(\theta)\rangle_N$, degenerate in the energy, are obtained, differing among themselves solely for the different value of the number N of condensed A_k and \tilde{A}_k couples: N acts as a code labeling these degenerate states.

At finite volume V , $|0(\theta)\rangle_N$ turns out to be a two-mode coherent state and can be represented as $|0(\theta)\rangle_N = \exp(-iG(\theta))|0\rangle$ with $G(\theta) = -i \sum_k \theta_k (A_k^\dagger \tilde{A}_k^\dagger - A_k \tilde{A}_k)$. Here A_k^\dagger and \tilde{A}_k^\dagger denote the creation operators.

Through Bogoliubov transformations, one may introduce also the annihilation (and creation) operators $A_k(\theta_k)$ and $\tilde{A}_k(\theta_k)$ for the state $|0(\theta)\rangle_N$. By minimizing the free energy functional for such a state one then finds the condensation density ${}_N\langle 0(\theta)|A_k^\dagger A_k|0(\theta)\rangle_N = N_{A_k} = \sinh^2 \theta_k = 1/(e^{\beta E_k} - 1)$ (and similar expression for $N_{\tilde{A}_k}$), namely the Bose-Einstein distribution for A_k (and \tilde{A}_k). Here $\beta = 1/T$, with T the temperature, and $E_k \equiv \omega_k$ (we use the Boltzmann constant $K_B = 1$ and $\hbar = 1 = c$). This relation shows the link between the condensate density (and thus the code N) and the set of θ_k parameters. Sets made by different θ_k values correspond to different condensation densities (different codes N , different ways or degrees of symmetry breaking, different memories).

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