A mesoscopic model for the collective dynamics of water coherence domains

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1. Introduction

It was back in 1916, when W. Nernst [1] first proposed that quantum fluctuations of elementary components of a physical system could be tuned together, in a collective oscillation, so that the many elementary components behave as a whole. This vision was theoretically grounded on Goldstone theorem and on the concept of spontaneous symmetry breaking [2]. Goldstone theorem states that, in presence of spontaneous symmetry breaking, collective phase excitations (phasons or phase solitons) are excited with no energy cost. If the symmetry is not exact, i.e. if it is explicitly broken as well as spontaneously broken, then the Goldstone mode activation has an energy cost, though it remains typically low. This is a very general scenario, observed in many physical systems. As an example, in magnetic materials the original rotational symmetry is spontaneously broken, when the magnetization points in a specific direction, the corresponding Goldstone collective excitations are the spin waves, in which the local magnetization direction oscillates. Prompted by the contributions of R. Peierls [3], E. Schrödinger [4], W. Pauli [5], H. Fröhlich [6] amongst many others, theoretical works as well as experimental evidences assessed that Nernst’s vision was able to describe peculiar (low-temperature) states of matter condensation, ranging from superfluidity in Bose-Einstein Condensation [7], to superconductivity in Fermi gases [8]. Indeed, at a low temperature, the collective phasons waves associated to low-energy-cost Goldstone modes can propagate and provide order in such different systems. This happens by means of an abrupt collective transition named phase transition [9], taking place at a critical temperature, that is quantified by a characteristic global order parameter, e.g. the magnetic susceptibility for magnetic ordering phase transition.

In the same context, Fröhlich [10] suggested a link between ordering Goldstone modes and biological coherence. In 1968, Fröhlich developed a quantum model aimed to describe the long-range coherence and energy storage in biological systems, by means of an analogy between
biological coherence and the long-range order found in a Bose gas [11]. Fröhlich’s model is still considered a reference in the field of quantum biology. E. Schrödinger, in his book “What is life?”, [12] quoted Nernst theorem as a mechanism to produce order from disorder, and he discussed its relevance for the emergence of life.

Recent studies, grounded on quantum electrodynamics, shed light on a specific phase transition able to induce long-range order in liquid water. It generally takes place in a large ensemble of electrically charged atoms/molecules, coupled with the quantum electromagnetic fluctuations of the vacuum [13]. In liquid water, an ensemble of $10^5 - 10^6$ H$_2$O molecules enters in a collective coherent oscillation between a pair of energy levels of its components, in tune with a non-vanishing quantum-fluctuating electromagnetic field, when the temperature is less than a critical threshold and the ensemble density exceeds a critical value. It happens because the energy of the coherent state is lower than the original non-coherent ensemble of components. This energy difference is termed *energy gap*. The existence of the energy gap accounts for the stability of the coherent state because, below the critical temperature, the energy supplied by thermal fluctuations is less than the energy gap so thermal fluctuations are unable to destroy the coherence. So liquid water spontaneously forms coherent mesoscopic spherical domains, termed Water Coherence Domains (WCDs), at room temperature, embedded in the residual bulk water made of fluctuating uncoherent H$_2$O molecules. The possible connection between those coherent states and the emergence of life is intriguing, because a coherent behaviour of water appears naturally related to biological coherence [14]. Indeed, the view of water as a morphogenetic agent, instead of a mere passive circulator is gaining increasing attention. Recently, a review of cases of a possible active role of water in the biogenetic process [15]–[17] has been proposed.

The quantum theory [18] predicts many features of WCDs, it states that the coherent internal oscillation of an ensemble of about $10^5 - 10^6$ H$_2$O molecules connects two electronic configurations that have the following features:

$|1\rangle$: The ground configuration, where all electrons are tightly bound (the ionization potential is 12.60 eV).

$|2\rangle$: The excited configuration, above a gap equal to $E = 12.06$ eV, just 0.54 eV below the ionization threshold. So, at room temperature, for each molecule there is an almost free electron.

The size of a WCD is of the order of 0.1 μm. The size of the region where molecules are entrained, corresponds to the wavelength of the electromagnetic mode responsible for the coherent oscillation, i.e. $\lambda = 0.1$ μm.
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Fig. 1 Sketch of the formation of a Water Coherent Domain (WCD) adapted from [19]. Above uncoherent water. Below, the formation of WCD. A further mechanism for establishing long range order between two adjacent WCDs, by evanescent wave coupling, is suggested. $F_c$ is the coherent fraction, i.e. how many water molecules are condensed in WCD in percentage. At room temperature $F_c = 40\%$.

When considering an ensemble of many WCDs, one could ask if/how higher order structures (patterns of WCDs) could emerge. Former works (as [19]) envisioned the possibility that WCDs could arrange in spatial arrays, by phase locking the surrounding electromagnetic waves, i.e. by evanescent wave coupling, similarly to what happens in optical systems (e.g. coupled waveguides and laser arrays [20]).

At room temperature, a fraction of the water molecule is ionized, so about $10^5 - 10^6$ free electrons are present in the spherical cavity. The trapped field pushes the free electrons to the periphery, forming a sort of orbital, and it pulls the ionized water molecules towards the centre of the sphere, forming a sort of nucleus. The so formed structure is a “giant atom”, a dipolar spherical structure. From the electromagnetic point of view, the WCD is a spherical capacitor of quantum nature, able to trap electromagnetic energy through coherence. However, magnetic effects could be important as well, as they are associated to rotational charge motion. Experiments showed angular momentum energy levels in the KHz range, reasonably associated to a finite magnetic momentum of the structure [21]. Experimental evidences also shown different kinds of supramolecular coherent water clusters, showing a variety of superstructures made of WCDs, snowflakes and
flexible rods amongst others [22].

Other experiments were aimed to connect water morphogenetic capacity to the emerging biological activity, mediated by electromagnetic waves [23]. In [23], some bacterial and viral DNA sequences have been found to induce low frequency electromagnetic waves in high aqueous dilutions. The process appeared to be triggered by a low frequency magnetic field. The biological relevance of (low frequency) magnetic field is well known [24] in general, but waves in [23] were specifically associated to objects about 100 nm of size, compatible with WCDs size. The nature of the waves was suggested to be superconductive, including non-linear waves as vortices induced by the magnetic field (20 -70 µT) naturally present on the Earth, with its first low frequency resonance, at about 7 Hz (Schumann resonance [25]). Because peripheral electrons in a WCD are almost free and collisionless, so they could easily acquire angular and magnetic momentum.

On the other hand, from a different background, Y. Kuramoto put forward a mathematical model [26], not in principle related to any real-world object, aimed to describe the collective synchronization of many mean-field coupled phase oscillators, each given a statistically distributed natural frequency [27]. The model is analytically solvable and provides a self-consistent expression for a collective order parameter, that shows a phase transition. In the Kuramoto model the role of temperature is played by oscillators diversity that acts as source of disorder. Diversity is measured by the standard deviation of the natural frequencies distribution.

Video 1. Click to watch. Video message from Yoshiki Kuramoto (Professor Emeritus, Kyoto University) to the international conference "Dynamics of Coupled Oscillators: 40 years of the Kuramoto Model" (Organizers: A. Pikovsky, A. Politi, and M. Rosenblum) held at the Max Planck Institute for the Physics of Complex Systems, Dresden, Germany on July 27, 2015. Prof. Kuramoto talks about the origin of his model and the its relationship with ferromagnetic phase transition and Ginzburg-Landau theory [28].

Despite of its theoretical derivation, Kuramoto model was surprisingly found able to describe many condensed matter problems, and biological systems. Kuramoto phase transition has been
associated to ferromagnetic materials critic behaviour, already described by former models, like the Ising model [29]. The relationship between Kuramoto model and, e.g. spin ordering in ferromagnets can be understood as follows. Kuramoto oscillators describe the dynamics of the phases of collective oscillatory modes. A visualization of the relationship between local spin precessions and collective wave phases is sketched in Fig. 2.

![Fig. 2. Local spin precessions (above) and phases of global oscillation (dashed line below).](image)

Also, superconductivity in Josephson junctions has been successfully related to Kuramoto model, as it concerns the collective entrainment of electronic waves phases [30]. Charge density waves, another Goldstone theorem related problem in structure of the matter, have been associated to the Kuramoto model too [31].

*The common ground between Kuramoto model and the phase transitions in condensed matter problems is the Goldstone theorem.* Kuramoto oscillators phases are indeed Goldstone modes, since each of them experiences a spontaneous symmetry breaking. Moreover, in the collective synchronization state, a new spontaneous symmetry breaking emerges, concerning the whole oscillators population. Because the entrained collectivity is a Kuramoto oscillator itself. This feature makes Kuramoto model suitable to describe self-organized *evolutionary* processes, as discussed in Sec. 5. The Kuramoto model also elucidated the core mechanisms of a wide range of biological phenomena, ranging from the rhythmic flashing of firefly congregations [32] to the coordinate firing of neurons or cardiac pace maker cells [33], inspiring (and being inspired by) researchers as Winfree to envision a *geometry of biological time* [34] as made of synchronizing/desynchronizing cycles. Synchronization emerged as a very general process [35], in the last decades, and Kuramoto model is an established paradigm for collective synchronization problems.

A recent work shows how global self-organized spatiotemporal patterns can come out of a disordered ensemble of point oscillators, as a result of a deterministic cooperative process
displayed by a modified Kuramoto model, including spatial degrees of freedom and oscillators polarity [36]. The standard deviation of the frequency distribution is the disorder parameter, called diversity and acting as temperature because it is both a source of motion and disorder. For zero and low diversity, robust static phase-synchronized patterns (crystals) appear. From small to moderate diversity crystals display vibrations, followed by structure disintegration in a competition of smaller dynamic patterns, internally synchronized, each of which is capable to manage its internal diversity. Here, a huge variety of self-organized dynamic shapes emerges. Such shapes (dynamics patterns) can be seen again as (more complex) oscillators, where the same description applied to the constituents of the patterns can be applied in turn to each pattern as a whole, renormalizing the problem to a bigger scale, enabling a nested multi-pattern self-growth. In this work, the possibility of applying the theoretical framework introduced in [36] to model the mesoscale cooperative dynamics of an ensemble of water coherence domains is investigated. This by means of a Heuristic modelling approach, based on symmetry considerations and dynamical systems theory.

The manuscript is organized as follows. In section 2 the derivation of a dissipative model for a single WCD is presented, and a physical interpretation is provided. In section 3, some results of the many body model for an ensemble of WCDs are summarized and interpreted in the light of a comparison with experimental phenomenology. Section 4 deals with cooperative behaviour after a frequency perturbation and inclusion of far – from – resonance elements. A sort of "metabolism" by cooperative behaviour is shown. Section 5 is devoted to a discuss the outcome of this work.

2. Mesoscopic modelling of a water coherence domain. The Giant Atom model.

“Each Coherent Domain of water is a resonating cavity produced by the electromagnetic field that ends up trapping the field [...]. The small spheres of water (‘balls’) that make up all the diverse structures of supramolecular water clusters created by Lo’s team have the dimensions of the coherent domains predicted, i.e., ~100 nm in diameter. [...] However, these spherical coherent domains are not dipoles in the ordinary sense of the word [...]” [22]
The symmetry of the Water Coherence Domain (WCD) structure suggests that peripheral free electrons could carry waves in the “lattice” formed by the periodicity of a peripheral circular cavity. Considering that, in general, most phases of matter can be understood through the lens of spontaneous symmetry breaking and Goldstone theorem, such theorem is the starting point of the theory.

Spontaneous symmetry breaking relays on the so-called Mexican Hat potential, sketched in Fig. 3, left panel. The geometry sketched in right panel of Fig. 3 contains a ring as a locus of minima in a Mexican Hat potential. Since a generic small perturbation relaxes to the ring, the dynamics can be limited to the ring. Supposing perfect circular continuous symmetry $U(1)$, the relative Goldstone mode is projected onto two generic counterpropagating travelling waves in the ring, with constant amplitudes and time varying phases $\varphi_+$ and $\varphi_-$. The resulting standing wave, superposition of the two counterpropagating travelling waves, does not have a constant amplitude, it alternates maxima and minima, and it is free to choose any position in the ring because there is no special point. When choosing a specific position, spontaneous symmetry breaking takes place, and phase solitons can be excited. The global phase $\Phi = \varphi_+ + \varphi_-$ can be ignored, as its dynamics becomes trivial in a proper rotating wave reference. However, the perfect circular symmetry never exists, and a point/region that makes the ring imperfect results in a phase locking of the two travelling waves in two specific wave profiles for the standing wave (whith phase $\varphi = \varphi_+ - \varphi_-$) one presenting a maximum, the other a minimum in correspondence of the imperfection, the former is favoured and the latter is disfavoured. In this case the U(1) symmetry is explicitly broken.
The red and blue lines are $\pi$-out of phase standing wave profiles, in presence of an impurity (black dot) that breaks the continuous circular symmetry (grey thick circle) in a remaining two-fold $Z_2$ discrete symmetry, represented by the dotted-line symmetry axes.

The presence of the imperfection makes the Mexican hat potential dependent on $\varphi$ in a periodic fashion, adding, at simplest, a potential term of the form

$$V_p(\varphi) = a \cos(\varphi), \quad (4)$$

where $a$ is a constant. The dynamics of the phase $\varphi$ is described by the following differential equation

$$\dot{\varphi} = -\frac{dV_p}{d\varphi} = a \sin \varphi. \quad (5)$$

The stationary solutions of Eq. (5) (fixed points) are twofold

1. $\varphi = 0$, often called in–phase solution, (marked here as $\uparrow\uparrow$ for a reason explained in the following paragraph).
2. $\varphi = \pi$, often called out–of–phase solution (marked here as $\uparrow\downarrow$). The stability of the two stationary solutions is given by the sign of $a$. Without losing generality, in the following is taken $a > 0$. This choice makes $\uparrow\downarrow$ stable and $\uparrow\uparrow$ unstable. In Eq. (5) modulus of $a$ can be rescaled with time, ending up with $a = 1$.

Eq. (4) states that the symmetry of the problem is reduced from the U(1) continuous group, when the Mexican Hat potential was independent on $\varphi$, to the two-fold $Z_2$ discrete group. The $Z_2$ discrete group is due to a remaining $\varphi \rightarrow -\varphi$ symmetry, which can be broken by a further term, a detuning $\Delta$, which represents a difference in the characteristic oscillation frequencies of the two counterpropagating waves. The presence of a detuning is a generic effect due to the different tangential phase velocities experienced by the two counterpropagating waves, and it modifies the potential (4) yielding
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\[ V_A(\varphi) = \cos(\varphi) - \Delta \varphi. \quad (6) \]

and

\[ \dot{\varphi} = -\frac{dV_A}{d\varphi} = \Delta + \sin \varphi. \quad (7) \]

Eq. (7) is the well-known Adler equation \[37\] or *overdamped pendulum*, a paradigm for two-mode locking problems. The detuning \( \Delta \) can activate periodic phase solitons in Eq. (7), via saddle-node bifurcation. Phase solitons represent the unlocking of the two counterpropagating waves, they are activated when the detuning exceeds a threshold, in this case for \( |\Delta| > 1 \), with period \( T \):

\[ T = \frac{2\pi}{\sqrt{\Delta^2 - 1}} \quad (8) \]

The period \( T \) approaches infinity as \( \Delta \to 1 \), indeed those phase solitons can be infinitely slow.

Fig. 5 shows as the potential \( V_A(\varphi) \) of Eq. (6) changes against \( \Delta \). When \( |\Delta| \) increases the potential barrier smoothens until, when \( |\Delta| > 1 \) the phase \( \varphi \) slides along the potential curve, which does not present local minima.

Fig. 5. Adler potential (6) \( V_A(\varphi) \) for a) \( \Delta = 0 \) b) \( \Delta = 0.5 \) c) \( \Delta = 1 \) d) \( \Delta = 1.5 \).

Each of the two waves \( \varphi_+ \) and \( \varphi_- \) is assumed to be associated to a *spatial degree of freedom* as sketched in Fig. 6. The result are two phase-points, each possessing two degrees of freedom: one spatial and a phase.
The idea is to model a WCD as a hybrid between a circular cavity and a dipole. As shown in Fig. 6, the dipole is represented by two symbols, a circle and a square, and their interaction is determined by symmetry requirements described below. The degrees of freedom reduce from four to two by considering that:

1. Only the phase difference \( \varphi = \varphi_+ - \varphi_- \), i.e. the standing wave phase, is important, as explained in the previous paragraph.
2. The trivial (null) dynamics of the mass centre can be neglected, since one spatial variable is relevant for two isolated objects: their relative position \( x \).

The potential function Eq. (4) is therefore modified including a generic differentiable function \( W(x) \), accounting for the dipolar interaction.

\[
V(x, \varphi) = W(x) \cos(\varphi). \quad (9)
\]

The potential (9) is required to fulfil the following 4-fold symmetry

\[
V(x, \varphi) = V(x, -\varphi) = V(-x, \varphi) = V(-x, -\varphi). \quad (10)
\]

So, \( W(x) \) must be an even function of the coordinates. Moreover, in order to have a stable structure, \( x = 0 \) has to be a stable stationary point for \( W(x) \), when \( x = 0 \) the dipole shrinks and disappears. Finally, any interaction is supposed to decay with distance. In summary, \( W(x) \) is asked to fulfil the following conditions:

\[
W(x) = W(-x), \quad (11)
\]

\[
W'(0) = 0, W''(0) > 0 \quad (12)
\]

\[
\lim_{x \to \infty} W(x) = 0. \quad (13)
\]
Requirements (11) – (13) basically shape the dipolar interaction function $W(x)$ as a finite potential well. In the following $W(x)$ is assumed to be the exponential well of Eq. (14), which specifies an interaction length $L = 1$, and depends on the distance between the phase-points. Polynomial decay has been considered as well, and the results are not qualitatively dependent on the specific choice of $W(x)$, provided that conditions (11) - (13) are fulfilled.

$$W(x) = -e^{-x^2}.$$  

(14)

Symmetry requirements (10) make the problem belong to a discrete cyclic abelian symmetry group that results isomorphous to $Z_4$, as direct product of two $Z_2$ subgroups. One $Z_2$ subgroup is associated to the $\phi \rightarrow - \phi$ symmetry, related to the arbitrary choice of the positive/negative angle measure, the other $Z_2$ subgroup is associated to the $x \rightarrow -x$ symmetry, i.e. the choice to call circle one point and square the other point is arbitrary and can be inverted, this subgroup is labelled as $c \rightarrow s$ symmetry in the following, $c$ meaning circle and $s$ meaning square. So, the group $\{c, s\} \times \{\phi_+, \phi_-\}$ is isomorphous to $Z_4$.

Those $Z_2$ symmetries are analogous (isomorphous) to the so called charge conjugation or $C$-symmetry, that reflects the arbitrary choice of calling $+$ or $-$ one charge sign, and to Parity ($P$) symmetry related to the arbitrary choice of calling “up” or “down” the spin orientation. The symmetry group of an electron-positron pair with spin (the most elemental “atomic” structure) is isomorphous to $Z_4$ too, for being the direct product of a $C$-symmetry ($Z_2$) and a Parity symmetry ($Z_2$). The two subgroups $C$ and $P$ form together what in physics is called CP-symmetry sketched in Fig. 7. So the $\{+, -\} \times \{\uparrow, \downarrow\}$ group is isomorphous to $Z_4$.

![Fig. 7. Sketch of the electron-positron pair with spin symmetry.](image-url)
The CP-symmetry states that the laws of physics should be the same if a particle is interchanged with its antiparticle (C-symmetry) while its spatial coordinates are inverted ("mirror" or P-symmetry). Electron spin is known to be P-invariant, as any momentum. Moreover, the Pauli exclusion principle forces two electrons to maximize the distance (Hund’s rule) with parallel spins, as sketched in Fig. 7.

![Interaction scheme](image)

Fig. 8. Interaction scheme, when phase-points of the same kind are interacting, the interaction is repulsive, because the in–phase solution, (↑↑) is unstable. When particles of different kind are interacting, the interaction is attractive because out–of–phase solution, (↑↓) is stable. This interaction scheme forms an “exclusion principle” analogous to Pauli exclusion principle sketched in Fig. 7.

In this sense the model for a WCD is called “giant atom” model, because the model ends possessing a symmetry group that is isomorphic to the symmetry group of an electron-positron pair with spin. The interaction between phase-points is conceived as shown in Fig. 8, and it shows a sort of “exclusion principle” as well. The interaction scheme shown in Fig. 8 is a consequence of the requirements (10) – (13) over the potential function. The stable stationary point at $x = 0$ is associated to the non-dipolar out-of-phase stationary solution for $\varphi = \pi$, which was marked as ↑↓ in the previous section, in analogy to electron spin. Such stable state $(0, ↑↓)$ appears at the bottom of a potential well, whereas $(0, ↑↑)$ at the top of a potential barrier, as shown in Fig. 9.

![Graphical representation of the potential function](image)

Fig. 9. Graphical representation of the potential function of Eq. (9).
If the $\varphi \to -\varphi$ symmetry is broken by a source of circular anisotropy representing a difference in the characteristic oscillation frequencies of the two counterpropagating waves. This creates a detuning $\Delta$ in the potential of Eq. (9), yielding

$$V(x, \varphi) = W(x) \cos(\varphi) - \Delta \varphi. \quad (15)$$

The equations of motions are derived as a dynamic dissipative system from (15), yielding

$$\dot{x} = -\frac{dV}{dx} = -W'(x) \cos(\varphi), \quad (16)$$
$$\dot{\varphi} = -\frac{dV}{d\varphi} = \Delta - W(x) \sin(\varphi). \quad (17)$$

If $\Delta \neq 0$ the $\varphi \to -\varphi$ symmetry is broken, so that the two phase-points are no longer equivalent, “parity” is broken, and phase waves can be excited.

Fig. 10. Potential function (8) in presence of circular anisotropy. Phase running solutions appear laterally outside the well. $\Delta = 0.15$.

Together with phase-waves, dipolar oscillations take place as well, associated to the dynamics of $x(t)$, when $\Delta$ exceeds a threshold [36]. It seems natural to define a complex variable $z = xe^{i\varphi}$ that describes phase waves and dipolar oscillations at the same time. Fig.11 shows various trajectories of $z$ in the complex plane, obtained by numerical integration of Eqs. (17)-(17) with different starting conditions. Left panel of Fig. 11 is for $\Delta=0$, so any starting condition drops to the stable steady state $(0, \uparrow \downarrow)$. Right panel of Fig. 11 shows various trajectories of $z$ when $\Delta = 0.5$. Those trajectories remain oscillating in closed orbits in the $z$-plane. These are phase waves, associated to dipolar oscillations as well.
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Fig. 11. Left panel: Some exemplificative trajectories of the complex variable $z$, solutions of Eqs. (16) - (17) for different starting conditions at $\Delta = 0$. Right panel: the same for $\Delta = 1.3$.

**Physical interpretation**

This work is based on the conjecture that a Water Coherence Domain (WCD) can support two counterpropagating waves, generating a standing wave pattern which phase $\phi$ displays a locking/unlocking transition. Such waves could be spin waves, other kinds of waves, but here they are generic Goldstone modes: “As a matter of fact, spin, electromagnetic and sound waves are, first of all, waves, i.e. medium oscillations transferred in a relay fashion from one point to another. If we are interested only in some propagation characteristics of the [...] waves, [...] then it is absolutely unnecessary to know what is it that oscillates, whether it is the magnetic moment, electric field, or density” [38].

The standing wave could slide along the lattice by means of phase solitons, if unlocked in some way, leading to a current proportional to $d\phi/dt$. In other words, the detuning $\Delta$ makes the two counterpropagating travelling waves *non-reciprocal*, i.e. they experience different phase velocities, similarly to the Sagnac effect for circular optical interferometers, an anisotropy in the directional propagation. Physically, such detuning could be related to the cyclotron frequency of the geomagnetic field, as envisioned by Montagnier and co-workers [23], and the Goldstone modes $\phi_+$ and $\phi_-$ could be related to the (global) phases of counterpropagating spin waves. In practice, the geomagnetic field could unlock two counterpropagating inherent Goldstone modes, of electromagnetic nature, associated to the presence of a U(1) symmetry in the single WCD. Such unlocking produces phase solitons in the ring intersection of the WCD sphere and the plane generated by the geomagnetic field.

Recent experiments [39] report on spin waves in nickel nanorings of 100 nm radius, showing an unlocking transition of counterpropagating spin waves at 50 mT of transverse magnetic field, at room temperature. Experiments showed different patterned spin-waves excited at different
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thresholds. However, the spin waves frequency versus the magnetic field intensity shows a behaviour analogous to the Adler frequency $f = 1/T$ versus the detuning $\Delta$, where $T$ is as in Eq. (8). A qualitative comparison is shown in Fig. 12.

![Graph](image)

Fig. 12. Left panel: Experimental Spin waves excitations in Nickel nano-rings, adapted from [39]. Right panel: Theoretical locking diagram. Frequency is $f = 1/T$, where $T$ is given by Eq. (8).

The experimental “dead-band” of 50 mT is due to electron-electron interactions, the form a “back-scattering” that locks the two counterpropagating spin waves. In a good metal the average interelectron distance is of the order of or smaller than the range of the interaction, e.g. the screening length is about 1 nm for typical parameters, because the carrier density is very high. The electronic cloud in a metal should be much denser than in a WCD, where the free-electron picture is expected to hold, and a much lower electron-electron interaction is expected.

In fact, temperature plays a crucial role in all the real-world Goldstone theorem related problems. The point is that thermal excitation hinders the long-range order, it destroys coherence, that is why e.g. superconductivity needs a very low temperature to emerge. On the other side, at low temperature, impurities prevent the waves from slipping along the crystal, by pinning phases to specific lattice positions. In a sufficiently pure WCD, the small symmetry breaking produced by the geomagnetic field could eventually produce coherent waves at room temperature. However, the proof of such conjecture goes beyond the possibility of the present Heuristic theory, that considers a WCD as a dual object made of two minimal complementary waves, two phase-points, which internal structure is ignored.

In the following section, some results concerning the extension of this theory to a many body problem are summarized. Those results are interpreted in the light of experimental phenomenology of WCDs.
3. The many-body problem and the phenomenology of Water Coherent Domains.

The previous section suggested that a Water Coherence Domain (WCD) might deform like a drop, a liquid electret, developing dipolar and phase oscillations of two complementary parts, due to a locking/unlocking bifurcation of two counterpropagating inherent Goldstone modes. Such complementary parts, phase-points, are the fundamental units of this theory. Extending the model to two interacting WCDs is already a highly complex problem, as it shows a huge variety of attractors, including stable and quasi-stable “isomers”, (different configurations of the 4-body problem), and a rich scenario of non-linear dynamics, multiperiodicity and chaos, because two distinct WCDs are not necessarily identical. Due to their quantum nature and to the eventual inclusion of impurities, WCDs can be reasonably supposed to carry a certain amount of diversity in the oscillation frequency, when considering many of them. This generates a modified Kuramoto model that undergoes a phase transition from order (synchronization) to disorder (desynchronization) depending on the degree of diversity present among the WCDs oscillation frequencies. The result [36] is a diversity induced phase transition, from long-range static “antiferromagnetic” ordered crystals at low diversity, to a disordered monomeric gas for high diversity, passing through a wide variety of emergent superstructures, combination of rotational and translational ordering. “Antiferromagnetic” here refers to the fact that π-phase jumps appear between next neighbours, in the low-diversity static patterns or crystals. Crystals take different shapes: snowflakes, rods or more complex structures depending on the number of implied elements and their diversity. For moderate diversity the crystals start to vibrate, developing internal pulsations that leads to structure fragmentation, progressively melting in a competition of dynamic patterns. The phases achieve dynamic states as well, developing deterministic waves, phase-waves, able to travel along the patterns. Indeed, when moderate diversity is included, a single static global pattern is no longer sustainable, and it breaks into smaller patterns, each of which is capable to manage its internal diversity. Increasing further the oscillators diversity the dynamics ends being erratic and disorganized, dynamic patterns show short lifetime and finally disappear. In the following a connection between the above described collective patterns dynamics and the coherent water clusters phenomenology is presented.

Experimentally, large Supramolecular Water Clusters were reported. [22] “Close-up, there appears to be a common fine structure to the clusters; they are all made up of small spheres tens of nanometres in diameter […] lined up in strings that are further aggregated into rods […]. These and other observations suggest to the researchers that the spheres are dipoles, enabling them to line up end to end to form an infinite variety of shapes and sizes”. [22]

In the following experimental results are compared to various outcomes of the many body model
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(some of them described in [36]). The left panel of Fig. 13 shows experimental “snowflake” structures and, besides, the result of a simulation with no-diversity, showing a similar spatial structure where phase points are arranged in an “antiferromagnetic” phase pattern.

Fig. 13. Left panel. Snowflake water mesoscopic patterns. Adapted from [22] Right panel: Movie 3: Click to watch. Result of a simulations of 33 phase points with no diversity, adapted from [36]. The pattern is static and overall synchronized to an “antiferromagnetic” phase pattern.

In order to show both spatial and phase dynamics, the phase is encoded in the colour of the phase points, according to what already done in [36]. The same colour corresponds to the same phase value. A grey trace is left as memory of the overall dynamics. Fig. 15 shows (left panel) an experimental evidence of organized mesoscale water patterns, made up by roughly aligned “dots”. Besides (Fig. 15 right panel) a simulation of 99 phase points with no diversity, showing spatial dots alignment in the “antiferromagnetic” phase pattern. Snowflakes and rods, or a mix of the two, are the simplest shapes displayed by few elements ensemble simulations. Simulations of the many-body problem with no-diversity show static patterns, always connected if the involved elements fall within the interaction length (which is also the characteristic length scale of the problem). When diversity is included in the problem, it triggers a dynamic activity in both phase and space. If diversity exceeds the critical value, the patterns start to have characteristic size and life-time themselves.
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Fig. 14. Left panel. Large supramolecular water pattern, experimental results. Adapted from [22]. Right panel. Regime configuration of a simulation of 99 phase-points with no diversity.

Fig. 15 (left and centre panel) shows the experimental evidence of the formation of a dynamic rod, apparently able to move. Fig. 15 (right panel) shows a simulation of 13 phase points with moderate diversity, with starting conditions falling within the interaction length. The result is the formation of two independent structures, displaying internal flow of phase-current, represented by color dynamics, and a rhythmic bending in space.

Fig. 15. Left and centre panel. Experimental water superstructures, adapted from [22]. Right panel. Movie 4. Click to watch. Numerical simulation of 13 phase points with moderate diversity, adapted from [36].

To investigate the phase dynamics, the spectra of each phase time trace concerning the simulation of Fig. 15 (right panel) has been numerically calculated and shown in a cumulative plot in Fig. 16 (left panel).
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Fig. 16. Left panel: Sum of the spectra of phase dynamics $\phi_n(t)$, $n = 1…13$, showing two peaks, each belonging to one of the two structures emerging in the movie of Fig. 15. Right Panel. Time evolution of the total kinetic energy of Eq. (10) in a logarithmic scale. Upper subpanel: from $t = 0$ to $t = 2000$. Lower subpanel: from $t = 4000$ to $t = 6000$.

The left panel of Fig. 16 shows two frequency peaks, each concerning one of the two emerging structures in the movie of Fig. 15. The two sneaky patterns are each internally synchronized and form out two new and more complex oscillators. The right panel of Fig. 16, shows the time evolution of the total kinetic energy, a time-dependent global quantity accounting for the mechanical motion in space, given by

$$E_k = \sum_{i=1}^{N} v_i^2,$$  \hspace{1cm} (10)

where $v_i$ are the particle velocities. After a transient, for $t > 800$ time steps, $E_k$ shows almost regular non-linear oscillations, associated to the rhythmic bending of the two structures.

Those emerging patterns are dissipative structures in the sense put forward by Prigogine [40]. Theoretically, because the many body problem is presented as a dissipative many body problem, including the first derivative of the degrees of freedom. Physically, because energy stored in the WCDs is dissipated by viscous interaction with bulk water when they move in the environment.

4. Frequency perturbation and inclusion of far - from - resonance elements by cooperative behaviour.

In [36], the robustness of the patterns respect to spatial perturbation was explored, showing a high degree of spatial robustness, i.e. the pattern, if broken, was able to self-reconstruct in adaptive fashion. So, in the following, an example of a phase-points ensemble including a single diverse element is shown. The following numerical experiment was performed. A small ensemble of 25
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A set of phase-point oscillators with no-diversity (all given the same natural frequency \( \omega \) set to zero) was numerically integrated from random initial conditions internal to the interaction zone (a circle of radius \( R = 1 \)). The ensemble initially develops a snowflake static “antiferromagnetic” pattern, as it appears in the first part of Movie 4 in Fig.17. At some point (\( t = 300 \)) the local frequency of one oscillator is raised to \( \omega = 7 \), with the aim of see the reaction of the system to such perturbation. The result is a highly engaged collective behaviour, were oscillators give the impression to develop a strategy aimed to finally include the different element by means of a collective dynamic. Equal oscillators make “use” of the different one to achieve a new pattern, quasi-static in space, where the different element is packed in the centre by the others. The right panel of Fig. 17 shows the time dependent kinetic energy. With no-diversity there is no motion, so initially \( E_k \rightarrow 0 \). The frequency perturbation makes all particles move, until, after the re-synchronization of the dissonant element, the \( E_k \) reaches a regime value. The re-synchronization process is investigated by examining the time-traces of the instantaneous frequencies \( \phi_n \), with \( n = 1...25 \), shown in Fig.18.

![Fig. 17. Left panel. Movie 5. Numerical simulations of 25 phase-points, initially with no diversity. After 300 time steps one element natural frequency is changed from 0 to 7. Right panel. Time evolution of total kinetic energy \( E_k \).](image)

Observing (see Fig. 19) the time traces of the oscillators instantaneous frequencies (or phase velocities) \( d\phi_j/dt \), \( (j = 1...N) \), four different regions can be identified regions.

A. **Initial synchronization.** The ensemble of 25 identical phase points develops a snowflake static pattern where \( d\phi_j/dt \rightarrow 0 \).

B. **De-Synch.** At \( t = 300 \), the frequency of one phase-point is raised from 0 to 7. The perturbed oscillator desynchronizes from the ensemble (orange line in Fig.18), whereas the remaining 24 oscillators keep a dynamic synchronization (cyan line in Fig.18). A process of frequency mirroring starts to take place enhancing the correlation between the time traces.

C. **Coherent information exchange by frequency modulation mirroring.** The 24 oscillators, which dynamics is entrained in a single time-trace (cyan line), though a closer look revealed slight differences (not visible in Fig. 18) in the 24 oscillators time traces. The different oscillator
(orange line) engages a sort of bit-based dynamics, correlated with the 24 oscillators traces glued together, mirroring the different oscillator frequency modulation.

**D. Re-Synch.** Mutual synchronization to a “compromise” frequency. The different element is integrated as far as synchronization is concerned. A new quasi-static pattern is globally formed (see Movie 5 in Fig. 17). The global kinetic energy $E_k$ reaches a steady state, whereas it was vanishing before the perturbation, as shown in the right panel of Fig. 17.

![Fig. 18. Time traces of the phase velocities of 25 identical phase-points initially forming a static pattern (region A). The natural frequency of one random element is changed from $\omega = 0$ to $\omega = 7$ at $t = 300$. This results in a destabilization of the whole pattern, where the system manages to reintegrate the different element, achieving again synchronization (region D) by a progressive mirroring of the phase velocities modulation (regions B and C). The 24 equal oscillators react as a dynamic whole, a collectivity that manage to entrain again the different element in a new pattern where the different element stays close to the centre, as if the pattern was organized revolving around it. It is worth noticing that the frequency synch takes place after about $t = 1000$ time steps, whereas kinetic energy $E_k$ reaches a stationary value much later, at about $t = 2000$ time steps. So, after $t = 1000$ the dynamics takes place in the synchronization manifold. The final synchronization is achieved by a progressive *mirroring* of the frequency modulation pattern, as shown in regions B and C of Fig. 18.

As an interpretation in terms of water coherence domains (WCDs), the WCDs can interact with other resonant objects eventually present in the neighbourhood, other WCDs or other compatible
structures. The above described cooperative dynamics could model the WCDs capacity to attract and conglomerate neighbouring objects, taking advantage of the frequency dissonance to generate kinetic motion. A precursor of a metabolic function. Resonant objects can be other WCDs or other chemical objects compatibles in term of size and electromagnetic properties, e.g. amino acids with different chirality and charge, proteins or viruses. According to Mae Wan Ho “This liquid crystalline water makes life possible by enabling proteins and nucleic acids to act as quantum molecular machines that transform and transfer energy [...]” [41]. The capability to manage far-from resonance object, and give them specific positions in the ensemble, could be helpful to understand the mechanism behind the so-called “Exclusion Zone”, where, next to hydrophilic surfaces the solute-free and solute-containing water can be separated naturally, without need for physical filters [42].

5. Discussion

The present work deals with a mesoscopic modelling of water coherence domains (WCDs), with emphasis on the collective properties of many of them. This approach qualitatively reproduces some features of the experimental phenomenology, and it could sustain an evolutionary theory based on layered synchronization processes.

The main element of novelty here is the straightforward use of dynamical system theory in a problem of structure of the matter, the historical realm of quantum mechanics. The reason of this choice is twofold. First, the idea is to focus on intermediate space and time scales, between the microscopic and the macroscopic world, the mesoscale. Having the size of a WCD (100 nm) as a point in the description, the theory appears naturally devoted to bigger space scales, i.e. greater than 1 µm. Secondly, the deterministic nature of dynamical system theory permits a different interpretation of the water condensate. A vision where each WCD has a definite trajectory, unique and different respect to others, due to its inherent diversity and to the deterministic nature of the theory. It is to say that the condensation of a Water Coherent Domain promotes a qualitative change in matter, from many indistinguishable statistical quantum particles, to one global self-propelled agent, able to perform complex cooperative tasks, following its own deterministic, though chaotic, individual trajectory. The subsequent pattern formation amongst many WCDs is therefore the result of a deterministic process of information exchange, not of a random motion. A process where cooperative agents perform decision making, and participate in aggregate communities by applying affinity criteria, i.e. to have or not a similar natural frequency, as a basic form of free-will. This reminds the resonant attraction criteria put forward by H. Fröhlich [43] and G. Preparata [13]. Still, the unpredictability of chaotic motion makes a high informational (high diversity) and highly noisy situations very similar from a statistical point of view.
An ensemble of diverse WCDs is seen as going through a diversity induced phase transition, that, due to its deterministic nature, discriminates coherence from information, instead that order from disorder. Highly coherent structures (low diversity) are robust and stable but not flexible to changes, so weakly adaptive. On the other hand, highly informative compounds (high diversity) require a chaotic motion to dynamically share information, resulting in unstable ephemeral structures. A compromise between coherence and information, close to the critical point, produces structures able to display a homeostatic growth by means of nested layers of synchronized Goldstone modes. Nested evolutive layers, internally synchronized, capable to behave as a whole and to form higher order structures, able to do the same again. Due to the increasing number of involved cooperative degrees of freedom, the complexity increases after passing from one evolutive layer to a higher one. Kuramoto model, due to its recursive spontaneous symmetry breaking, is a suitable tool for describing that. Close to the critical diversity, many dynamical patterns, competing self-organized structures emerge. Each pattern can be seen again as a (more complex) oscillator, able to synchronize in turn to similar structures at a bigger scale, tolerating a certain amount of diversity, and so forth. The process repeats itself, causing the spontaneous evolution of a Chinese box of nested self-organized structures, overall coherent, that can attain decades of order of magnitudes of length and time scales.

The emergence and evolution of life is seen here as a coherent organizational flux, able to take advantage of the convenient geometric possibilities, by walking a path of Goldstone modes spontaneously present at different scales, a low-energy path, where the energy generated by ordering the Goldstone modes is higher that the energy required to do it. This energetic surplus permits an evolutive flow against entropy. The vision introduced in this work is in some respects similar to Fröhlich’s, although his methodological realization was radically different. He suggested that the biological order proceeds from the transition to coherence of Goldstone modes, a process similar to the Bose-Einstein Condensate (BEC) or magnetic ordering. The Kuramoto model is about the same idea, as it describes the collective synchronization of phase (Goldstone) modes, and it describes BEC and magnetic ordering too, together with several biological processes.

Physically, Kuramoto Goldstone modes, as far as WCD condensation and its possible relevance for the emergence of life are concerned, could be related to magnetic ordering. “[...] we have found that brief exposures of early fruitfly embryos to weak static magnetic fields cause characteristic global perturbations to the segmental body pattern of the larvae emerging 24 hours later. As the energies involved are well below thermal threshold, our conclusion was that there can be no effect unless the external field is acting on a coherent domain where charges are moving in phase, or magnetically sensitive dipoles undergoing phase alignment globally.” [44]. The symmetry breaking that causes phase solitons and pattern dynamics in WCDs could be associated to the magnetic field spontaneously present on the Earth, as suggested by Montagnier and co-
workers [23]. The emerging patterns would be self-driven by the magnetic energy trapped inside trough coherence.

This work is in line with cognitive theories put forward by Varela and Maturana [45]. On the ontological level, the present work deals with a transformation of brute matter, by condensation, into self-organized agents. A transformation from undifferentiated objects unintentionally moved by fluctuations, to diverse agents, energetically independent, moved towards other beings by affinity criteria. A transformation suitable to describe the emergence of life, seen as a transition concerning the nature and relations of beings, rather than their material structure,
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