On the interaction of extreme-low-frequency (ELF) radiation with living matter’s coherent spiral states

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Abstract.

Conventional physics cannot explain bioeffects caused by ELF fields [1]. A (double) resonance interaction of ELF radiation with the highly sub-thermal coherent motion of spiral waves in living matter (LM) is suggested. The (geo)magnetic cyclotron resonance (CR) absorption by the constituent ions can drastically change their non-thermal degrees of freedom in the spiral state, destroying their pattern, which is heuristically assumed to be part of the cell signaling. Combining ELF irradiation with calcium imaging to unravel the suggested mechanism, a new instrument in biomedicine might emerge. These fascinating waves, being part of the bio-machinery, might provide insight in cancer, embryogenesis, etc., as they are affected by ELF radiation in an as yet unknown manner [2-6].
1. Introduction

There is a general agreement that the ubiquitous in modern civilization nonionizing ELF electromagnetic fields induce a variety of physiological and cellular responses (e.g. [4–10]). Concerns have been raised that they are carcinogenic and leukegenic [1, 11]. The underlying interaction with LM is considered to be too weak for us to expect a significant effect at the cellular level, since such effects are usually associated with the breaking of molecular bonds of macromolecules like DNA [1]. The characteristic quantum energy $h\nu_{ELF} \approx 10^{-14}$ eV of the ELF-radiation (e.g. 50 or 60 Hz) is far too below the thermal energy ($kT \approx 2.4 \cdot 10^{-2}$ eV), or, much worse, the chemical binding energy (a few eV), to disrupt the genetic code. The thermal noise fields, in the vicinity of cells, are $\sim 100 - 1000$ times stronger than that associated with the external ELF field [3], which is composed, in the classical picture, of quasi-independent electric and magnetic field components. Therefore, the question remains, how do cells recognize the existence of the primary weak signal? [2]. One arrived to the conclusion that a fundamental understanding of the (as yet unknown [2–6]) interaction mechanism of ELF fields inducing biological effects must be found outside conventional physics [1]. That is to say, the most natural conclusion is that there cannot be biological actions by weak ELF fields [4, 12], contradicting experimental results showing their impact on DNA, RNA and protein synthesis, $Ca^{++}$ regulation, dynamics of cell division, embryogenesis, etc. [13–17], including biomineralization in vitro [18].

Lowest external perturbations may trigger bioeffects, as LM functions under conditions far from equilibrium [15, 19]. Some proposals to solve this signal-to-noise problem are mentioned: a) stochastic resonance at the driving frequency and its harmonics, i.e. weak signal amplification by the system noise itself [2], b) cells average out the thermal noise by integrating the signals, with the estimated integration time being $\sim 10$ times longer than exposure intervals observed to produce bioeffects [20], c) cells discriminate against the spatially random thermal noise fields by recognizing them (somehow) as spatially incoherent [6]: the data show that a (temporally coherent) 100 Hz field causes abnormal embryogenesis, being blocked by a superimposed noise field ($\sim 10 - 400$ Hz), and d) the weak fields couple to receptor-controlled cytosolic calcium oscillator, being stabilized far away from thermal equilibrium, predicting specific intracellular calcium oscillations [15]. This list of ideas is by no means exhaustive (e.g. [21]).

In this work an interaction mechanism between ELF radiation and LM is described, which can be directly established combining known experimental methods, introducing possibly a new technique in biomedicine.
2. Spiral waves

Excitable media in (bio)chemistry being initially in a spatially uniform steady state can reach and maintain spontaneously a far-from-equilibrium non-uniform 2D or 3D spatiotemporal order [22]; they are characterized by their ability to propagate signals undamped over long distances at the expense of (chemical) energy stored in the medium. A rotating spiral wave [22], with inward turning tip (inner endpoint) and outward moving fronts, is the 2D cross section through the real 3D scroll wave, which emanates from an organizing closed axis.

In biology, rotating spiral waves have been observed in numerous cases [22-25]: in retinal and cortical nerve nets, in heart and muscular tissue, in the lenses of the eye of a firefly, but also in the aggregation of cells [19, 26], as well as, in fungi culture growth and sporulation (with circadian or sub-circadian biorhythms) [27]. Ca++ wave development has been observed even at the level of a single cell [28]. Calcium couples extracellular stimuli to cellular responses in virtually all cell types [29]; the most obvious function of calcium waves is to carry calcium signals deep into the cells [30]. However, the exact mechanism of Ca++ signaling that mediates cell communication remains one of the most intriguing mysteries in biology [31]. The frequency and amplitude of the propagating Ca++ waves (remarkably constant for individual cells) potentially contains additional encoded information [31, 32, 33]. Furthermore, cell-specific unique patterns of transient Ca++ signals have been termed ‘Ca++ fingerprint’, being possibly implicated in complex processes such as spatial cellular specialization, cellular differentiation, and information storage [32, 34]. A Ca++ transient, which initiates development during fertilization, takes also the form of wave or oscillation [35].

Typical values for the velocity of propagation, wavelength and frequency of spiral waves in LM, are \( v \approx 10 - 100 \mu m/s \), \( \lambda \approx 10 - 1000 \mu m \) and \( \nu \approx 0.1 - 10 \) Hz, respectively (e.g. [30, 31, 36, 37]). The resonance response of spiral waves to the modulation frequency of an external stimulus and its harmonics [38] can in addition enhance the interaction with varying weakest irradiation.

3. The suggested interaction mechanism

Inorganic ions like \( Ca^{++}, K^+, Na^+, Mg^{++}, Cl^- \), etc. make \( \sim 1 \% \) of the total cell weight. Ion transport is related to cell signaling in many ways [3]. Throughout this work for reasons of simplicity, numerical examples refer to ionized calcium, which is the most common signal transduction element in cells ranging from bacteria to specialized
neurons [31]. Spiral waves of this ubiquitous second messenger (Ca++) in LM are of particular interest, since their collective (≈ coherent) rotation frequency is within the range of the ion’s CR frequency [39]:

$$\omega_{\text{cyclotron}} = 2\pi \nu_{\text{cyclotron}} = \frac{qB}{M} \approx 40 \text{ Hz}$$  (1)

for Ca++ being inside the static (geo)magnetic field $B \approx 0.5$ gauss ($M =$ ion mass). The excessive large orbit of the gyrating ions and the collisions with the surrounding medium [1] make a classical description of CR meaningless. In the quantum picture [39], considering the excitation of quasi-quantum states (= Landau Levels), the photon energy is transformed first into kinetic energy of the gyrating ion; those long-lived states [39] are actually not deexcited radiatively, as they give their energy to the environment during collisions.

The gyroresonance frequency (relation (1)) refers to an ideal case, with the incident photons moving parallel to the guide magnetic field ($B$), otherwise only the parallel field component contributes. Inside the ubiquitous static geomagnetic field, LM is exposed to a rather isotropic ELF irradiation coming from the power lines, but also from geomagnetic activity [40]. Relation (1) provides the upper limit of the fundamental frequency. For example: a) the measured width of the gyroresonance signal, e.g. the variation of the cell-motility as a function of the frequency of the incident electromagnetic radiation [41], is a wide Lorentzian shaped distribution at the expected CR frequency of Ca++ at $\omega_{\text{cyclotron}} = 16$ Hz for $B = 0.209$ gauss, with FWHM $\approx 6$ Hz, b) a weak 16 Hz irradiation in combination with a 0.234 gauss parallel static field, i.e. also at the Ca++ gyroresonance frequency, provided an inhibition of calcium influx in thymocytes [42], and c) an enhancement of Ca++ uptake by normal and malignant lymphocytes was observed at 13.6 Hz (near the CR for Ca++) [43]. Thus, the gyroresonance interaction and its higher harmonics with the Ca++ ions alone inside the geomagnetic field ($\approx 0.5$ gauss) can occur actually at any frequency below $\sim 10 - 100$ Hz. However, energy transfer from the weak ELF radiation to LM via the CR absorption was also considered to be negligibly small, as the thermal Brownian-like motion overwhelms by factor $\sim 10^{12}$ any (orbital) gyromotion [4]. Afterall, the CR interaction probability reaches unitarity, as the resonance cross section in the classical or quantum picture is enormously high: $\sigma^{CR} \approx \pi \lambda_{\text{ELF}}^2$ [39]. Thus, the CR interaction alone provides primarily the necessary mechanism to efficiently couple the ELF radiation to LM’s ions.

The spiral wave spinning frequency in LM is, surprisingly, within the geomagnetic CR frequency range of the constituent ions. Moreover, it occasionally occurs that the ELF field is simultaneously also at resonance with the spiral coherent macroscopic rotation.
Although such a potential double resonance can further enhance the interaction [38], its occurrence is not absolutely necessary (s. below). The fundamental question to be addressed is how this coupling overcomes the very unfavourable thermal energy. Note that the propagation of $Ca^{++}$ waves is an active process, not solely the result of passive calcium diffusion [14]. Along with ref. [15], those degrees of freedom which govern these spiral states must be at least partially decoupled from the rest of the system, which might well be in thermodynamic equilibrium. Only then, the following amazing numerical estimations, or conclusions, make sense (relations (2)−(4)). Remarkably, inside an environment with a mean thermal energy $kT \approx 10^{-2} \text{ eV}$ per atom or molecule or ion, the constituent ions of the coherent spiral motion appear to propagate at an almost constant velocity ($v$) taken to be typically [30]

$$v = v_{spiral} \approx 50 \mu m/s,$$

(2)

which should correspond to a kinetic energy of a $Ca^{++}$ ion following the collective spiral motion of

$$T^{Ca}_{kin} = \frac{1}{2}Mv^2 \approx 0.5 \cdot 10^{-15} \text{ eV}.$$  

(3)

This means that the spiral-ions keep a coherent velocity component ($v = v_{spiral}$), which is slower than their thermal velocity in the surrounding medium ($v_{th} \approx 3.5 \cdot 10^4 \text{ cm/s}$), by a factor $\sim 10^7$. To put it differently, it is as if one could assign to the spiral’s constituents an effective temperature ($kT^{effective} \approx T^{Ca}_{kin}$), being far below the thermal equilibrium:

$$T^{effective} \approx 10^{-10} - 10^{-13} \text{ K}$$

(4)

for $v \approx (5 - 200) \mu m/s$ [30], while being inside an environment approximately at room temperature (!). Moreover, due to the peculiar spiral motion, the participating ions appear finally not to move randomly relative to each other, since their velocity is highly correlated, as they are driven by the common spiral wave. Bearing in mind that cryogenic thermal detectors in dark matter search, work in the $\sim mK$ range [15], one should expect a very high sensitivity of this form of macroscopic ‘frozen’ states inside LM to external signals.

Let us consider the CR absorption of one single ELF radiation quantum by a $Ca^{++}$ ion belonging to a spiral wave, taken the earth’s magnetic field as the guide field for the CR interaction. One single photon energy ($\approx 10^{-14} \text{ eV}$), being transformed to gyromotion (= kinetic energy) of an ion, changes obviously its coherent motion and the associated kinetic energy ($\approx 0.5 \cdot 10^{-15} \text{ eV}$) completely. This is still true even for initially quite higher $Ca^{++}$ velocities, e.g. $v \approx 200 \mu m/s$. Furthermore, assuming a much higher spiral velocity, or, a much weaker guide magnetic field for the CR to occur, the resonance
absorption of several ELF field quanta per ion can take place because of the enormous high CR cross section involved; therefore, they also can change finally the ion’s collective velocity, disturbing or even destroying the fascinating biochemical spatiotemporal order. This hypothetical case shows that the spiral wave can be disturbed, even if its intrinsic frequency is not in resonance with the ELF field; of course, if it happens to be the case probably the impact due to the double resonance will be even stronger.

*In short*: only spiral states, stabilized (= ‘frozen’) far below the thermal equilibrium, can drastically be changed by the weakest ELF CR photon absorption, disturbing thus this form of signal transmission, provided the wave’s coherent degrees of freedom are decoupled from the thermal ones. With spirals being involved in LM’s fine tuned machinery, and, having in mind the plethora of cellular events $Ca^{++}$ controls (e.g. proliferation of many cell types [43, 46]), it is not unreasonable to expect all kinds of biological malfunction, once its pattern has been externally modified.

4. Discussion - Suggestion

The spontaneous appearance in LM of spatiotemporally ordered states, which move collectively as spinning and occasionally as drifting spirals with characteristic rotation frequency and at a very slow (not random) velocity of propagation, distinguishes all excitable media in the living and the non-living world. This work combines the known properties of the fascinating spiral waves, which dominate biology, with the (geomagnetic) cyclotron resonance interaction of the constituent ions without inventing necessarily new physics. The observed impact of ELF radiation on the calcium metabolism of the cell may be due to changes caused in the calcium waves involved. It has been recognized already how important unraveling the multiple roles played by $Ca^{++}$ will be, e.g. in regulation of cell proliferation [46].

In conclusion the following suggestions are underlined: a) there are (highly developed) experimental techniques to make the heuristically assumed response of the $Ca^{++}$ waves to ELF radiation, or to modulated electromagnetic irradiation at the spiral’s own frequency, ‘visible’; this can be achieved, for example, by the use of fluorescence imaging and confocal microscopy with $\sim \mu m$ and $\sim ms$, space and time resolution, respectively [30, 35, 17, 18, 49]. Such a direct observation, being the paramount component of this work, could reconcile the mystery surrounding the connection between ELF fields and the biological observations, establishing thus the role of spiral waves in biocommunication, b) via the ELF irradiation of LM, one should also search for any difference between normal and malignant cells, which could be utilized to selectively interact ex-
ternally with the cancer cells only, and c) the spiral multicellular morphogenesis may be considered a very primitive form of embryogenesis, where cell differentiation might be associated with enhanced signaling. Bearing in mind the observed abnormalities due to ELF irradiation during embryogenesis [16], another direct piece of evidence of the impact of ELF radiation on spiral waves could be derived from the study of the multicellular aggregation [26], or fungi culture growth [27], under ELF irradiation. The striking macroscopic spirals appearing in those investigations simplify the experiment enormously.

Thus, the ELF irradiation in combination with existing biological methods may become a new probe, providing possibly access to microscopic biological phenomena. One may finally gain insight into open issues like embryogenesis, cell signaling and differentiation, biorhythmicity, etc. Similar experiments performed with excitable media from the non-living world, can be helpful, as spiral waves are strongly affected by just a few V/cm static electric fields [50].
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