

## Review

# Physical Differences between Man-Made and Cosmic Microwave Electromagnetic Radiation and Their Exposure Limits, and Radiofrequencies as Generators of Biotoxic Free Radicals

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**Simple Summary:** There is an inconsistency between the position that radio frequencies are sources of minor thermal effects in cells, tissues and living organisms and the experimental evidence indicating that non-ionising radiation is harmful, even at shallow power density radiation levels. A quantum mechanical survey of the interaction between microwaves and matter points to free radical-associated cytotoxic alterations of biomatter upon microwave irradiation.

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**Abstract:** The critical arguments for radiofrequency radiation exposure limits are currently based on the principle that radio frequencies (RF) and electromagnetic fields (EMFs) are non-ionising, and their exposure limits are even 100-fold lower than those emitted from the Sun in the whole RF-EMF spectrum. Nonetheless, this argument has been challenged by numerous experimental and theoretical studies on the diverse biological effects of RF-EMF at much lower power density ( $W/m^2$ ) levels than today's exposing limits. On the other hand, less attention has been given to counterarguments based on the differences in the physics concepts underlying man-made versus natural electromagnetic radiation (EMR) and on the fact that man's biology has been adapted to the natural EMR levels reaching Earth's surface at single EMF wavelengths, which are the natural limits of man's exposure to EMFs. The article highlights the main points of interaction of natural and man-made radiation with biomatter and reveals the physical theoretical background that explains the effects of man-made microwave radiation on biological matter. Moreover, the article extends its analysis on experimental quantum effects, establishing the "ionising-like" effects of man-made microwave radiation on biological matter.

**Keywords:** natural/man-made EMF; ELF/RF EMR; natural vs. man-made exposure limits; EMR biological effects

## 1. Introduction

Electromagnetic radiation (EMR) emits and transmits energy waves travelling through a vacuum or matter from packets of different frequency (energy) photons. Oscillating electric charges mainly generate EMR. The flow of waves in Space creates local and time-changing magnetic and electric fields. Many researchers argue that man-made EMR is potentially biologically harmful [1–3] because it differs from natural radiation (mainly originating from the Sun). Natural EMR is filtered mainly by Earth's atmosphere, allowing man's biology to adapt to shallow levels of radiation reaching the Earth's surface. Natural EMR is electromagnetic (EM) waves covering a broad spectral range of

wavelengths (mainly  $\lambda > 0.01$  nm), including the UV, visible (the Sun's spectral power density maximum emission), infrared, X- and gamma-rays. Furthermore, EMR is emitted by Earth's electric fields (developing between the ionosphere and Earth's surface) and from the Schumann resonances, the ultra-low frequency (7.83 Hz) window [4]. Besides the Sun, visible light is also emitted from flames and artificial lamps, such as the light-emitting diodes (LED) used by Visible Light Communications (VLC) and Optical Fibre Communications (OFC) technologies.

Earth's magnetosphere and ionosphere are protective shields against the deadly cosmic radiation (fast-moving electrons) coming from Space. Electromagnetic fields (EMFs) are also blocked by the Earth's atmosphere at microwave frequencies. As a result, only shallow levels, similar to 2G-5G man-made radiation sources emitted by the Sun, reach Earth's surface. In contrast, Earth's atmosphere transmits visible and infrared light and Schumann resonances, suggesting that human biology might be incompatible with the anthropogenic RF-EMF [5–7], because humans and other organisms have adapted well to the cosmic radiation background by synchronizing their biological clocks accordingly [8]. Natural evolution permits humans to tolerate and use visible photons to regulate the melatonin cycle or synthesise vitamin D from UV-A radiation as our eyes have adapted to visible light. Moreover, specific frequencies of natural EMFs are exploited by trillions of cells within the human body for intercommunications, e.g., the waves  $\alpha$  (8–12 Hz),  $\beta$  (13–30 Hz),  $\Delta$  (1–4 Hz) and  $\theta$  (4–8 Hz) are used for heartbeat regulation, the nervous system's neural signals, and electrical activities of the brain. Naturally, the evolution of man's biology has adapted only to the cosmic EMFs that reach Earth's surface.

Man's exposure shifted from the cosmic background to the man-made EMR environment in 1882 when the first man-made EMFs started emitting from the high voltage cables of the first commercial power plant in the U.S., the Pearl Street Station plant, which powered lower Manhattan [9]. Today, the global expansion of wireless communication—a development of military applications since the 1960s—exposes the global community to RF-EMF (2G–5G) radiation many orders of magnitude above the natural exposure limit at a single wavelength. The following facts support the argument:

According to Planck's law, the power density  $I(\nu, T)$  per solid angle ( $Sr$ ) and per frequency  $\nu$  (Hz) emitted from the Sun's surface, approximated as a black body, depends on the frequency of the emitted radiation and the Sun's surface temperature  $T \sim 5.5 \times 10^3$  K, and is given by,

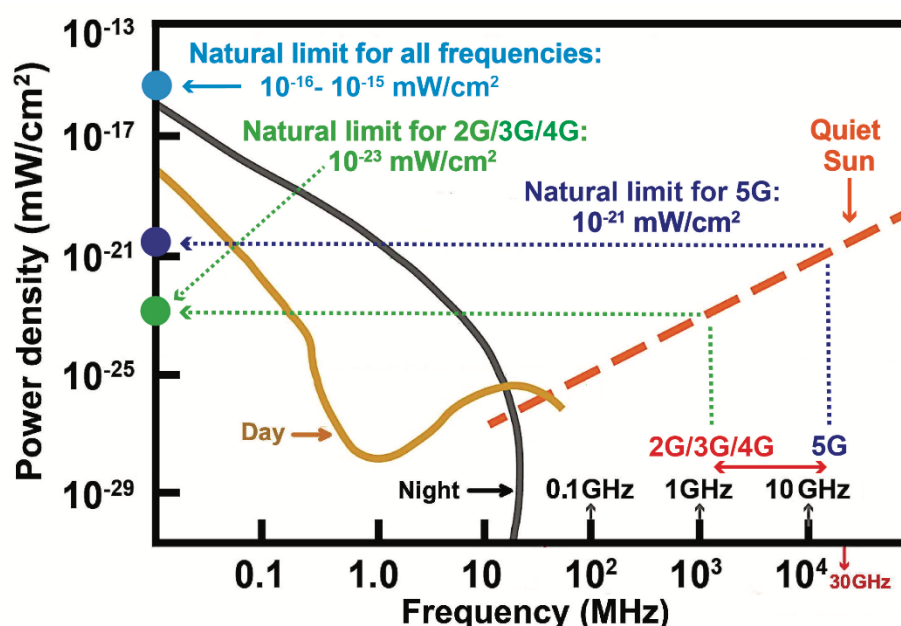
$$I(\nu, T) = 2 \frac{h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \left( \frac{\Delta\nu}{2} \right) \quad (1)$$

where  $h = 6.626 \times 10^{-34}$  Js is Planck's constant,  $K$  is Boltzmann's constant equal to  $1.39 \times 10^{-23}$  JK<sup>-1</sup>,  $\frac{\Delta\nu}{2}$  is the bandwidth at full width at half-maximum (FWHM) at the emitted frequency  $\nu$ . For the conditions applied at the Sun's surface, it is plausible to consider  $\Delta\nu$  to be the thermal Doppler broadening at the emitted frequency,

$$\Delta\nu = \sqrt{\frac{8KT \ln 2}{mc^2}} \nu \quad (2)$$

where  $m$  is the helium atom mass equal to  $1.67 \times 10^{-27}$  Kg, and  $c = 3 \times 10^8$  ms<sup>-1</sup> is the speed of light. Finally,  $\Delta\nu = 5.2 \times 10^{-3} \nu$ . From Equations (1) and (2), the cosmic EMR microwave background energy density at, e.g., 2.4 GHz, emitted from the Sun's surface per solid angle is  $\sim 10^{-11}$  Wm<sup>-2</sup> Sr<sup>-1</sup>. For an average Sun-to-Earth distance  $r = 1.5 \times 10^{11}$  m and a Sun's radius  $R = 6.7 \times 10^8$  m, the average solid angle  $\Omega$  of the Sun viewed from the Earth's distance  $r$  ( $\Omega = \pi r^2/R^2$ ) is  $\sim 6.26 \times 10^{-5}$  Sr. From Equations (1) and (2), the radiation power density from the Sun reaching the Earth's surface at 2.4 GHz is  $\sim 10^{-16}$  W/m<sup>-2</sup> ( $\sim 10^{-17}$  mW/cm<sup>2</sup>). The Sun's theoretically calculated value of radiation power density at microwave frequencies reaching the Earth at a point near the Earth's orbit in Space is seven

orders of magnitude higher than NASA's measured power density on the Earth's surface at 2.4 GHz [10], which is equal to  $\sim 10^{-23}$  W/m<sup>2</sup> ( $\sim 10^{-24}$  mW/cm<sup>2</sup>) (Figure 1). The difference between the measured and theoretical value of power density is possibly due to radiation scattering by cosmic particles, small-size bodies and plasma in the Space area between the Sun and the Earth. The experimentally measured natural microwave levels for the non-ionising cosmic EMF spectrum associated with the 2G–5G wireless frequencies ( $\sim 0.8$  to 12 GHz) at the Earth's surface lay between  $\sim 10^{-22}$  and  $10^{-20}$  W/m<sup>2</sup> ( $\sim 10^{-23}$  to  $10^{-21}$  mW/cm<sup>2</sup>), Figure 1. The above cosmic microwave radiation levels at the specific frequencies are biologically safe because of the adaption of organisms through natural evolution over billions of years on Earth's surface. These natural cosmic radiation levels, being the natural biological exposure limits, can be compared to the 10 W/m<sup>2</sup> (1 mW/cm<sup>2</sup> or  $10^4$  mW/m<sup>2</sup>) microwave and radiofrequency exposure limit set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the U.S. Federal Communications Commission (FCC), at 30 min for whole body exposure and 6 min for local exposure for not developing any thermal damage [11,12]; further information can be found elsewhere [13]. Finally, the conclusion is that for the whole frequency spectrum from 2G to 5G, the ICNIRP/FCC exposure limit recommendation for man-made EMR is  $\sim 10^{21}$  to  $10^{23}$ -fold higher than the average radiation background of the Sun's non-ionising radiation at Earth's surface in the 2G–5G spectral range.



**Figure 1.** Day and night natural limit of power density (mW/cm<sup>2</sup>) of EMR emitted by the Sun and reaching Earth's surface in the microwave spectral regions, from 0.1 to  $3 \times 10^4$  MHz. The associated power density natural limit of  $\sim 10^{-23}$  to  $10^{-21}$  mW/cm<sup>2</sup> is compared with the ICNIRP exposure limit of  $\sim 1$  mW/cm<sup>2</sup> for man-made microwave sources. The ICNIRP/FCC thermal exposure limit for man-made EMR is  $\sim 10^{21}$ - to  $10^{23}$ -fold higher than the natural microwave radiation limit at Earth's surface of single microwave frequencies from the Sun (the plot is an extensive modification of that in NASA's report CR 166661 [10]).

The global community's RF-EMF radiation exposure issues can be practically understood using the EMF emission power density of a typical Global System for Mobile Communications (GSM) cellular tower base station [14,15]. Taking the least harmful exposure scenario for a citizen at a distance of 1 Km from a GSM tower antenna, the average exposure radiation power density is  $10^{-6}$  W/m<sup>2</sup> ( $10^{-7}$  mW/cm<sup>2</sup>) and  $2 \times 10^{-7}$  W/m<sup>2</sup> ( $2 \times 10^{-8}$  mW/cm<sup>2</sup>) when in line and not in line, respectively [14]. Even in this most favourable case,

the radiation levels are  $10^{13}$  to  $10^{15}$ -fold higher than the natural exposure EMF limit. Furthermore, microwave radiation's thermal and non-thermal interaction with materials is still debatable. Up to now, non-thermal effects are wrongly and misleadingly viewed as being caused only by ionisation (where an atom/molecule acquires a negative/positive charge by gaining/losing electrons), ignoring that microwave frequencies generate free radicals from molecular bond braking via dissociative excited electronic states. In the case of water, experimental results indicate long-term changes in the structure of water after the microwave treatment. The mechanism of this effect today is not entirely clear, although several factors rendered, including the formation of hot spots, development, and the increased dipole moment of the reacting molecules in the transition state compared to the initial state [16,17].

In this communication, biological effects from microwave radiation are viewed under the light of non-thermal microwave interaction with the matter based on Chirikov ionisation localisation [18], microwave absorption and microwave trapping between rotational molecular levels [19], and quantum microwave trapping between coherent symmetric and antisymmetric water cluster states [20–23]. The theoretical and experimental background emphasises the discrepancy of microwave exposure levels between the cosmic power density of microwave radiation emitted mainly from the Sun and reaching the Earth's surface and today's existing radiation exposure limits, designed to protect from thermal effects.

## 2. Man-Made Versus Natural EMF Radiation and Corresponding Microwave Power Density Exposure Limits

Frequency  $\nu$  or wavelength  $\lambda$  characterises EMF waves and photons, and their energy is proportional to their frequency according to Planck's formula  $E = h\nu$ , where  $h$  is Planck's constant. Each photon has its own electric and magnetic fields, the intensities of which are at a fixed ratio, and their vectors are perpendicular to each other and the direction of the photon's propagation at far distances from the emitting sources. In addition, each photon is polarised in the direction of the electrical field vector. The physical characteristics of each photon define its dual character as a photon and an EM wave.

EM waves (photons) emitted from natural sources (Sun) are uncorrelated. They exist as independent and incoherent EM waves because their photons' phases are not linked. The Sun's total radiation power density reaching Earth's surface in the whole emission spectral frequency range is  $\sim 1400 \text{ W/m}^2$  ( $140 \text{ mW/cm}^2$ ) (in Western, Central, and Eastern Europe around noon and a clear sky [24]), and is scaled proportionally to the number of photons. In contrast, the energy of an artificial (man-made) coherent EM beam falling on a surface is scaled as the square of the number of photons compared with the linear scaling of an incoherent photon source [25].

The Sun's EMFs reaching the Earth's surface penetrate human and animal skin, and individual EMR photons are partly reflected, absorbed and converted to heat. The worst-case scenario for humans from the Sun's radiation reaching the Earth is melanoma after prolonged exposure to the UV part of the Sun's radiation.

Man-made EMFs might also affect biological activity because their physical properties are quite different from natural EMF/EMR [26,27]. Artificial "non-ionizing" EMFs, including those emitted by mobile phone base stations, WiFi, etc., mainly cover the spectral range from 300 kHz to 30 GHz. Additionally, the low-frequency (LF) range waves from 3 to  $3 \times 10^3 \text{ Hz}$  ( $10^5$  to 10 Km) are generated by oscillating currents in metal wires (e.g., antennas, power lines). Artificial EMFs are emitted as *near-field* and *far-field* radiating modes (with a short transient transmission interval in between) according to the ratio of the distance to the wavelength.

The *near-field* is the EMF segment emitted from an antenna or a power line wire at a distance equal to one wavelength. The near-field itself is further divided into the *reactive near-field* and the *radiative near-field*, both fractional functions of wavelength. The reactive near-field is extended at a distance of  $0.159 \lambda$  from the antenna. The *radiative near-field*

(Fresnel region) covers the remainder of the *near-field* region at a distance of one wavelength. *Near-field* RF-EMF is a complicated space mathematical multipole structure of electric and magnetic fields, mutually independent with no fixed ratio intensities. For the 3G–4G systems, a transmission distance equal to one wavelength follows the *radiative near-field* length [28,29].

In contrast, *far-field* dipole-type EMFs produce a fixed phase relationship between electric and magnetic components [28,29]. Consequently, RF *near-fields* do not emit standard coherent or incoherent EMFs. However, a phase locking of individual waves and possibly non-linear photon interactions with matter make *near-fields* potentially harmful to man [1]. For example, in the 3G (1.8–2.5 GHz) and 4G (2–8 GHz) wireless communications RF bands, the carrier frequencies range from just under 1 GHz to just over 2 GHz (above 0.3 to below 0.15 m, respectively), and the average *near-field* length is 0.225 m. Therefore, when someone holds a smartphone next to its ear or a laptop/tablet at a distance less than 0.225 m, the head and some more sensitive body parts are exposed to the *near-field*, and, possibly, humans experience harmful biological effects [30–32].

In the Extremely Low Frequency (ELF) spectrum, the most predominant frequencies are those emitted by the high voltage power lines acting as antennas of alternating currents at 50 or 60 Hz, frequencies that correspond to *near-field* lengths of  $6 \times 10^6$  or  $5 \times 10^6$  m, respectively. Therefore, the power lines' electric and magnetic field components behave independently for long distances and bear variable intensity ratios. When no power is consumed, the power lines emit constant electrical fields. However, as the current flows across the power lines at a variable strength (because of variable power consumption), it generates a variable strength magnetic field (proportional to the fluctuating current intensity). Nonetheless, in the range of *near-field* distances, the electric and magnetic fields act independently for possible biological effects [33,34]. ELF electric fields penetrate living tissues with a certain degree of attenuation, and magnetic fields penetrate with almost zero attenuation. Based on statistical and laboratory shreds of evidence, the International Agency for Research on Cancer (IARC) has classified both ELF magnetic fields and RF-EMFs as possibly carcinogenic to humans [33,35].

It is commonly claimed that the small electric absorption depth of the human skin prevents electric and magnetic fields from penetrating the body. However, this argument is not physically justified. The electromagnetic field is a dual entity with an electric and a magnetic component, simultaneously created by the time-variable electric charges and currents. However, the elaboration of the differential coupling equations of electric and magnetic fields propagated in dielectric, diamagnetic or paramagnetic media suggests that neither Maxwell's equations nor their solutions indicate continuous and constant causal links between the fields. Instead, they only form a dual entity of an electric and a magnetic component, created by their time-variable electric charges and currents [36]. Along the above theoretical lines, it has also been documented that the magnetic field component of artificial EMFs is biologically active [37–41]. Therefore, the emphasis on electric field intensity (V/m)-based on current recommended radiation exposure limits underestimates the biological effects caused by the cumulative magnetic EMF component that primarily penetrates the human body [42,43]. Furthermore, constant or *far-field* magnetic field components increase carcinogenic free radicals' cellular levels via the free radical pair spin flipping mechanism [35,44] and/or via coherent trapping of microwave radiation in rotational levels of water clusters [20,21].

Furthermore, man-made RF-EMF *far-fields* are produced additively by individual EMF photons as being coherent or partially coherent with each other. RF-EMF *far-fields* are produced by photons fully synchronised to each other (in a frequency, polarization, phase, pulse, and propagation direction). In contrast to the non-synchronised photons emitted by the Sun, the intensities of man-made individual electric and magnetic fields add up coherently or partially coherent, conditions that make them possibly biologically active since coherent photons are cumulative on a macroscopic scale; thus, they possess the potency to form cores of biological effects over exposing time [42,45,46].

The following section discusses the effect of “Chirikov localisation”, which refers to the microwave ionisation of hydrogen atoms.

### 3. The Physical Basis of Microwave Interaction with Matter

#### 3.1. Microwave Adiabatic Tunnelling Ionisation

Electric and magnetic fields penetrate through the skin, even with low penetrating skin-depths. Consequently, the RF-EMF induces electrical currents, resonant interactions and interferences on charged/polar and magnetic particles, cell membrane surfaces and free radical pairs, thus leading to potential biological effects [44,47,48]. Similarly, ELF EMF induces voltage differences, currents and magnetic field effects on the membranous components of human cells [48].

The principal counterargument is that RF-EMFs are non-ionizing, and their effects are only thermal. The counterargument is based on the fact that the EMR photons are not energetic enough to break the bonds holding organic molecules together. However, many biological environmental interactions originate from non-ionising electric fields [49–54], such as cancer proliferation from radiation-polarised dielectric nanoparticles [47]. Most importantly, the non-ionisation-based argument of “no-biological” effects is weakened by the microwave excitation and ionisation of hydrogen atoms known as *microwave adiabatic tunnelling*, the most striking and less known effect of the destructive ionic interaction of the “non-ionising” microwave frequencies with the matter. Indeed, today it is commonly known that high-energy ionising UV radiation induces bond breaks in organic and biological matter via excited dissociative electronic molecular states, populated from the ground electronic state via one-photon absorption. For example, the binding energy of the C–C bond is 3.6 eV, and the two carbon molecules can be separated from each other (by covalent bond homolytic split) upon irradiation with one photon at 345 nm [55]. Molecular bond breaking by photons is the reason why UV radiation is biologically harmful [56,57]. At shorter photon wavelengths or higher photon energies, the excess photon energy is compensated as kinetic energy of photofragments, causing localised mechanical damages. In contrast, the common misconception about microwave photons, e.g., at 2.4 GHz, is that they are theoretically unable to break molecular bonds or ionise atoms. However, striking gas ionisation experiments with low amplitude photons at ~1 and ~10 GHz [58] demonstrated that the ionisation of the hydrogen atom exited first with laser light at a principal quantum number  $n = 69$ . The excited electronic level with  $n = 69$  is separated from the ionisation continuum of hydrogen by  $7.57 \times 10^{-4}$  eV. Therefore, at 1 ( $4.134 \times 10^{-6}$  eV) and 2.4 GHz ( $9.921 \times 10^{-6}$  eV), 183 and 76 photons from the electronic level with  $n = 69$  ionise the hydrogen atom, arguing against the idea that microwave interaction with matter is only thermal and, thus, against the thermal basis of the current RF-EMF exposure limits.

Given that adiabatic tunnelling breaks the electron-proton binding energy in the hydrogen atom [58] and that RF-EMF photons can provide this energy in the 2G–5G range, it can be expected that microwave adiabatic tunnelling will provide the cumulative RF photons needed to split the antiparallel spin electron pair holding the O–H bond in H<sub>2</sub>O of 1.88 eV (117.61 Kcal/mol) [59,60], and generate hydroxyl ( $\bullet$ OH) and hydrogen ( $\bullet$ H) free radicals. Therefore, photons at the 2G–5G spectral range could provide free radicals with biological and medical implications for man’s health [61].

Microwave ionisation is viewed as *adiabatic quantum mechanical electron tunnelling* through a time-varying potential barrier produced by the Coulomb and the external forces of the microwave field exerted on the atom. Electron tunnelling occurs when the conditions  $T > \tau$  and  $E < E_0$  are satisfied, where  $T$  is the ratio of the microwave interaction with the atom,  $\tau$  is the electron period around the nucleus, and  $E$  and  $E_0$  are the strengths of the microwave and the atomic Coulomb field, respectively. The adiabatic parameter  $\gamma = \nu/nE$  describes the ionisation tunnelling for  $\gamma < 1$ , while the condition of  $\gamma > 1$  covers any possible combination of parameters. Strong ionisation occurs at relatively weak field

amplitudes, several times smaller than the static field ionisation threshold. Delone et al. described the microwave excitation and ionisation by an energy diffusion equation using random phase approximation [62], and along the same lines, Meerson et al. [63] gave a correct estimation of the ionisation threshold based on the Chirikov criterion of resonance [18]. In this approximation, the classical diffusion equation describes the photonic transitions and quantum interference effects count for the localisation length and the number of photons [64–66]. Additional references and results for the microwave ionisation of excited atoms can be found in past reviews [67–69]. Arndt et al. also provided additional experimental work on Rydberg atoms' microwave ionisation [70]. The “Chirikov localisation” refers to the discovery and investigation of microwave ionisation by Boris Chirikov [18]. This chaotic diffusion can be localised by quantum interference effects and is similar to the Anderson localisation [71], which appears in disordered solids when a diffusive spreading in space existing for classical trajectories becomes exponentially localised due to quantum interference effects. Chirikov localisation stresses the dynamical origin of this phenomenon emerging without any disorder.

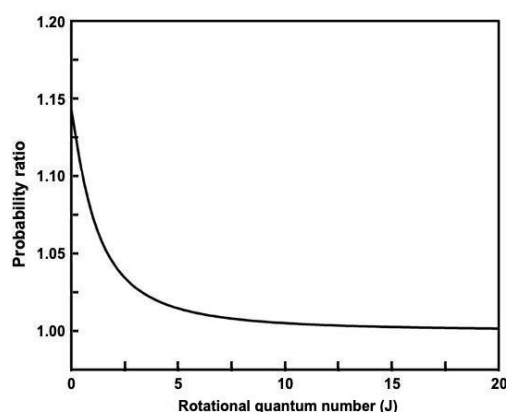
### 3.2. Absorption of RF-EMF by Biological Matter and Water

Besides microwave tunnelling adiabatic ionisation, a destructive molecular mechanism is the microwave interaction with the rotational levels of molecules or their clusters [20,22,48]. The quantum theory of microwave spectroscopy developed by Townes and Schawlow [19] verifies that the absorption probability of EMF between two rotational molecular states with an energy difference close to the energy of the microwave radiation is higher than the relaxation probability of the excited, energetic quantum state to the lower energy state. For a particular symmetric-top molecule, similar to a water molecule in an initial quantum state  $|J M\rangle$ , the absorption and emission probabilities  $\gamma_{J,M \rightarrow J+1,M}, \gamma_{J+1,M \rightarrow J,M}$  between the quantum states  $J, M \rightarrow J+1, M$  and  $J+1, M \rightarrow J, M$  are given by the expressions,

$$\gamma_{J,M \rightarrow J+1,M} = \frac{2\pi h^2 N f_v}{9c(kT)^2 B} \sqrt{\frac{\pi Ch}{kT}} \mu^2 \frac{(4J+3)(J+2)}{(J+1)^2} \frac{v_0^2 v^2 \Delta v}{(v-v_0)^2 + \Delta v^2 + \tau^{-2}} \quad (3)$$

$$\gamma_{J+1,M \rightarrow J,M} = \frac{2\pi h^2 N f_v}{9c(kT)^2 B} \sqrt{\frac{\pi Ch}{kT}} \mu^2 \frac{(4J+7)(J+3)}{(J+2)^2} \frac{v_0^2 v^2 \Delta v}{(v-v_0)^2 + \Delta v^2 + \tau^{-2}} \quad (4)$$

For an averaging over all the magnetic quantum numbers  $M$  of a particular rotational angular momentum state  $J$ .  $J$  and  $M$  are the rotational and magnetic quantum numbers,  $N$  is the number of molecules per unit volume,  $f_v = e^{-\frac{\varepsilon}{kT}}(1 - e^{-\frac{\varepsilon}{kT}})$  is the fraction of molecules in a particular vibrational state of energy  $\varepsilon = h\omega_e(v + \frac{1}{2})$ ,  $k = 1.38 \times 10^{-23} \text{ JK}^{-1}$  is the Boltzmann's constant,  $B = \frac{h}{8\pi^2 I_B}$  and  $C = \frac{h}{8\pi^2 I_C}$  are the rotational constants,  $I_B, I_C$  are the molecular moments of inertia along the molecular axes  $x, y$  and  $z$ , respectively,  $\mu^2$  is the square of the dipole moment matrix element,  $v_0^2$  is the resonant frequency or the central frequency of the absorption line,  $\Delta v$  is the half-width of the absorption line at FWHM,  $c$  is the velocity of light,  $T$  is the absolute temperature, and  $\tau^{-2}$  is the collision dephasing time during a molecular rotation. From Equations (3) and (4), the absorption probability of radiation at microwave frequencies by molecular rotational levels is higher than the emission probability between higher and lower rotational states with similar quantum numbers. This result must be valid to maintain thermal equilibrium when transitions occur, since there are  $2J+3$  states of rotational angular momentum  $J+1$ . Therefore, it is evident that microwave electromagnetic energy is stored in rotational states. The storage efficiency falls with the increasing quantum number (Figure 2).



**Figure 2.** The ratio of absorption to emission probability of microwave radiation from molecular rotational states as a function of the rotational quantum number  $J$ . Resonance of microwave radiation with the rotational levels of water clusters or resonances via microwave adiabatic tunnelling is responsible for microwave energy trapping between the rotational energy levels of water clusters, causing biological stress during the interaction of EMR with biological matter.

The rotational frequencies of water molecules and clusters lay in the terahertz and microwave spectral bands, respectively. For example, the rotational frequency of water molecules at 2.466454 THz stands for terahertz resonance of water molecules with quantum numbers  $J = 6$  and  $M = 4$ . Similarly, the operation of a microwave oven in the microwave spectral region, coming as a result of preferred size (e.g., at 2.4 GHz), is based on the resonance between microwave radiation and the rotational levels of large molecules and water clusters, implying that electromagnetic energy can be stored on rotationally excited quantum states of water clusters. To specify the limits of the energy spectrum for electromagnetic interaction with the rotational levels in the first approximation, we consider that the separation between nuclei in linear rotating molecules is fixed. The possible frequencies of the end-over-end rotation of this “molecular rigid rotor” can be obtained. Using assumptions of the “old” quantum mechanics, the angular momentum of the rotating molecular system must be some integral multiple of  $\hbar/2\pi$ , and hence the rotational frequencies expected from the system are,

$$\nu = \frac{h}{2\pi^2 I} J(J+1) \quad (5)$$

where  $h = 1.056 \times 10^{-34}$  Js is Planck’s constant,  $\nu$  is the frequency of rotation,  $I$  is the molecular moment of inertia about the axes perpendicular to the internuclear axis, and  $J$  is a positive integer, giving the angular momentum in  $\frac{\hbar}{2\pi}$  units. For the  $\bullet\text{OH}$  free radical, the moment of inertia ( $I = 1.27 \times 10^{-47}$  kgm<sup>2</sup>) comes from the nuclei mass and the molecular separating distance of  $9.7 \times 10^{-11}$  m. For small integral values  $J$  between 1 and 10, the rotation frequency  $\nu$  lies between 0.2 and 11 GHz, and therefore the rotational levels of the  $\bullet\text{OH}$  molecules are potentially in resonance with the 2G to 5G frequencies, and EMF energy storage is potentially possible. This strengthens the suggestion, made in sub-Section 3.1, for a plausible  $\bullet\text{OH}$  generation from splitting the O–H bond in H<sub>2</sub>O by RF-EMF photons in the 2G–5G range.

When exposed to the radiation level of, e.g.,  $10^{-3}$  mW/m<sup>2</sup> ( $10^{-4}$  mW/cm<sup>2</sup>) at 1.8 GHz ( $10^4$ -fold lower than the ICNIRP/FCC limit), emitted by, e.g., a GSM tower located ~100 m far away [14], the number of fully synchronised photons per s and m<sup>2</sup> that bombards the human body is  $\sim 8.4 \times 10^{20}$  [72,73]. Therefore, because of the microwave energy-storing effect [19], the biologically harmful effects from antenna power stations can immensely increase for the billions of people exposed every day to about 10 W/m<sup>2</sup> (1 mW/cm<sup>2</sup>), which is today’s microwave exposure limit, or to about a specific absorption rate (SAR) of radiation of 0.125 W m<sup>2</sup>kg<sup>-1</sup> for an 80 kg heavy person. This effect is even more profound when holding a mobile phone against the ear, generating a microwave power density of 1 W/m<sup>2</sup>



(0.1 W/m<sup>2</sup>) in the cranium area that is equivalent to a higher SAR value of about 0.222 W m<sup>2</sup>kg<sup>-1</sup> for an average human head weighing 4.5 kg. An even more significant concern is for children's still-developing small size brains. As Dr. Vriens aptly points out: "Saying that the RF radiation from wireless communication cannot do any harm because the individual photon energies are not large enough is the same as saying that a tsunami cannot cause any harm because the individual water molecules do not have enough energy" [74].

### 3.3. Microwave Interaction with Symmetric and Antisymmetric Water Cluster States

A plethora of CaCO<sub>3</sub> precipitation experiments under the application of external magnetic fields in water flow systems verifies that CaCO<sub>3</sub> precipitates in the form of aragonite than calcite, which is the crystal form of CaCO<sub>3</sub>, at standard conditions and zero magnetic fields. CaCO<sub>3</sub> precipitants appear in three different crystal forms, and the one with the lower ground electronic state is the rhombohedral calcite. Aragonite has a lower symmetry and belongs to the orthorhombic crystal group. A less stable form of CaCO<sub>3</sub> is the hexagonal vaterite, which undergoes a crystal phase transition to calcite or aragonite. Because the ground electronic energy state of aragonite is ~0.8 eV above the ground electronic state of calcite, CaCO<sub>3</sub> precipitates as calcite at room temperature. However, theoretical and experimental results also show that CaCO<sub>3</sub> aragonite precipitates at low magnetic fields of 50 mT because the magnetic field modes can become trapped in an ensemble of coherent antisymmetric quantum rotating states of water molecules, in resonance with the magnetic field modes [22]. By applying second quantisation for the magnetic field and the rotating water molecular rotors, where both systems are described as ensembles of interacting vibrations, the interaction Hamiltonian in the dipole moment approximation between the magnetic field and the molecular rotors is given by

$$\hat{H}_I = g \sum_{k\lambda} 2((\hat{i} - \hat{j}) \hat{\sigma}_{\omega R} \hat{a}_{k\lambda}^+ (\exp(-\omega_k t) + 2(\hat{i} + \hat{j}) \hat{\sigma}_{\omega R} \hat{a}_{k\lambda}^+ (\exp(\omega_k t) \quad (6)$$

where  $\hat{a}_{k\lambda}^+$  is the creation operator of the magnetic field modes for the polarization  $\lambda$  and mode  $k$ , and  $\hat{\sigma}_{\omega R}$  is the annihilation operator for the molecular rotational mode  $R$  at frequency  $\omega$ . The summation over  $\lambda, k$  is for all the molecular rotors and the magnetic field modes. By changing the notation, Equation (6) is simplified to

$$\hat{H}_I = g \sum_{\lambda, k} (\hat{\sigma}_{\lambda}^+ \hat{a}_k + \hat{\sigma}_{\lambda} \hat{a}_k^+) \quad (7)$$

At time  $t = 0$ , the quantum state of an ensemble of molecular rotors by the wavefunction  $|\Psi(0)\rangle$ . When the magnetic field is switched on, the wavefunction of the system at time  $t$  becomes

$$|\Psi(t)\rangle = \hat{U}(t, 0) |\Psi(0)\rangle \quad (8)$$

where  $\hat{U}(t, 0)$  is the Dyson time ordering operator. The first-order approximation of the operator is

$$\hat{U}(t, 0)^{(1)} = 1 - \frac{1}{\hbar} \int_0^t dt_1 H_I(t_1) = 1 - g t (\sigma_{\lambda}^+ \hat{a}_k + \hat{\sigma}_{\lambda} \hat{a}_k^+) \quad (9)$$

The wavefunction  $|\Psi(0)\rangle$  is the product of molecular rotor  $|\Psi(0)\rangle_{MR}$  and magnetic field wavefunctions magnetic field  $|\Psi(0)\rangle_{MF}$ . The ground and the excited states of one two-level molecular rotor, say the  $n^{\text{th}}$  rotor, will be  $|b\rangle_n$  and  $|c\rangle_n$  respectively. If the molecular rotors do not interact, the total wavefunction is

$$|\Psi(0)\rangle_{MR} = |b_1\rangle |b_2\rangle \dots |b_n\rangle = |b_1 b_2 \dots b_n\rangle \quad (10)$$

For  $N$  modes of the magnetic field, and in case the  $j^{\text{th}}$  mode is in resonance with one molecular rotor, the wavefunction of the MF  $|\Psi(0)\rangle_{MF}$  is

$$|\Psi(0)\rangle_{MF} = |1\rangle \dots |j-1\rangle |j+1\rangle \dots |N\rangle = |1, 2, \dots, j-1, 0, j+1, \dots, N\rangle \quad (11)$$

Because the molecular rotor has absorbed the  $j$  mode, the total wavefunction of the system is

$$|\Psi(0)\rangle = |b_1 b_2 \dots b_n\rangle |1, 2, \dots, j-1, 0, j+1, \dots, N\rangle \quad (12)$$

In a first-order approximation at time  $t$ , the wavefunction of the system is

$$|\Psi^1(t)\rangle = |\Psi(0)\rangle - \frac{i}{\hbar} g t \sum_{\lambda, k} (\hat{\sigma}_\lambda^+ \hat{a}_k + \hat{\sigma}_\lambda \hat{a}_k^+) |\Psi(0)\rangle \quad (13)$$

Allowing for the action of both the creation and annihilation operators, Equation (13) becomes

$$|\Psi^1(t)\rangle = \sum_j^N A_j |b_1 b_2 \dots b_n\rangle |1, 2, \dots, j-1, 0, j+1, \dots, N\rangle \quad (14)$$

Equation (14) describes a quantum state where the  $j^{\text{th}}$  molecular rotor in the ensemble absorbs one magnetic field mode. The coefficients  $A_j$  are either negative or positive, and therefore  $|\Psi^1(t)\rangle$  will be either symmetric or antisymmetric. The conclusion is that the first-order perturbation of the system creates a set of symmetric and antisymmetric quantum states of the ensemble of molecular rotors. When  $N_b$  rotors are in the ground state and  $N_c$  in the excited state, then the molecular rotors will absorb  $N_c$  magnetic field modes. In this case, the wavefunction should be approximated to the  $N_c^{\text{th}}$  order of the  $\hat{U}(t, 0)$ . Allowing for all the existing permutations, the number of states is

$$|N_c\rangle = \left(\frac{N!}{N_c! N_b!}\right)^{-\frac{1}{2}} \sum_{perm} A_n (-1)^n |b_1 b_2 \dots b_b c_{b+1} \dots c_N\rangle |1, 2, \dots, b\rangle \quad (15)$$

The coefficient  $A_n (-1)^n$  is a function of the normalisation conditions. If all the coefficients are positive, the states are symmetric. The system is in a Dicke state, and the interaction between the molecular rotors and the magnetic field is similar to the super fluorescent interactions in laser systems. For an even number of negative coefficients, the states are antisymmetric. The decay probability  $P_{abs}$  of a magnetic field mode absorbed by the  $j^{\text{th}}$  molecular rotor will be proportional to the matrix element

$$P_{abs} = \langle N_{c-1} | \hat{\sigma}_j | N_c \rangle \quad (16)$$

If only one of the  $\langle N_{c-1} |, \langle N_c |$  states is antisymmetric, the transition probability is zero, and therefore the magnetic field mode is trapped between the coherent antisymmetric state and the coherent ground state of the ensemble, in agreement with Equations (3) and (4).

The quantum cyclotron resonance effect is similar to the ion cyclotron resonance effect in Zhadin [75]. Therefore, the aragonite precipitation can be interpreted as the magnetic vector quantum states being trapped and amplified between a pair of coherent symmetric and antisymmetric quantum states formed by individual water molecular rotors under the action of the external EMF [20]. The coherent symmetric and antisymmetric states are similar to the theory of coherent domains [21,23].

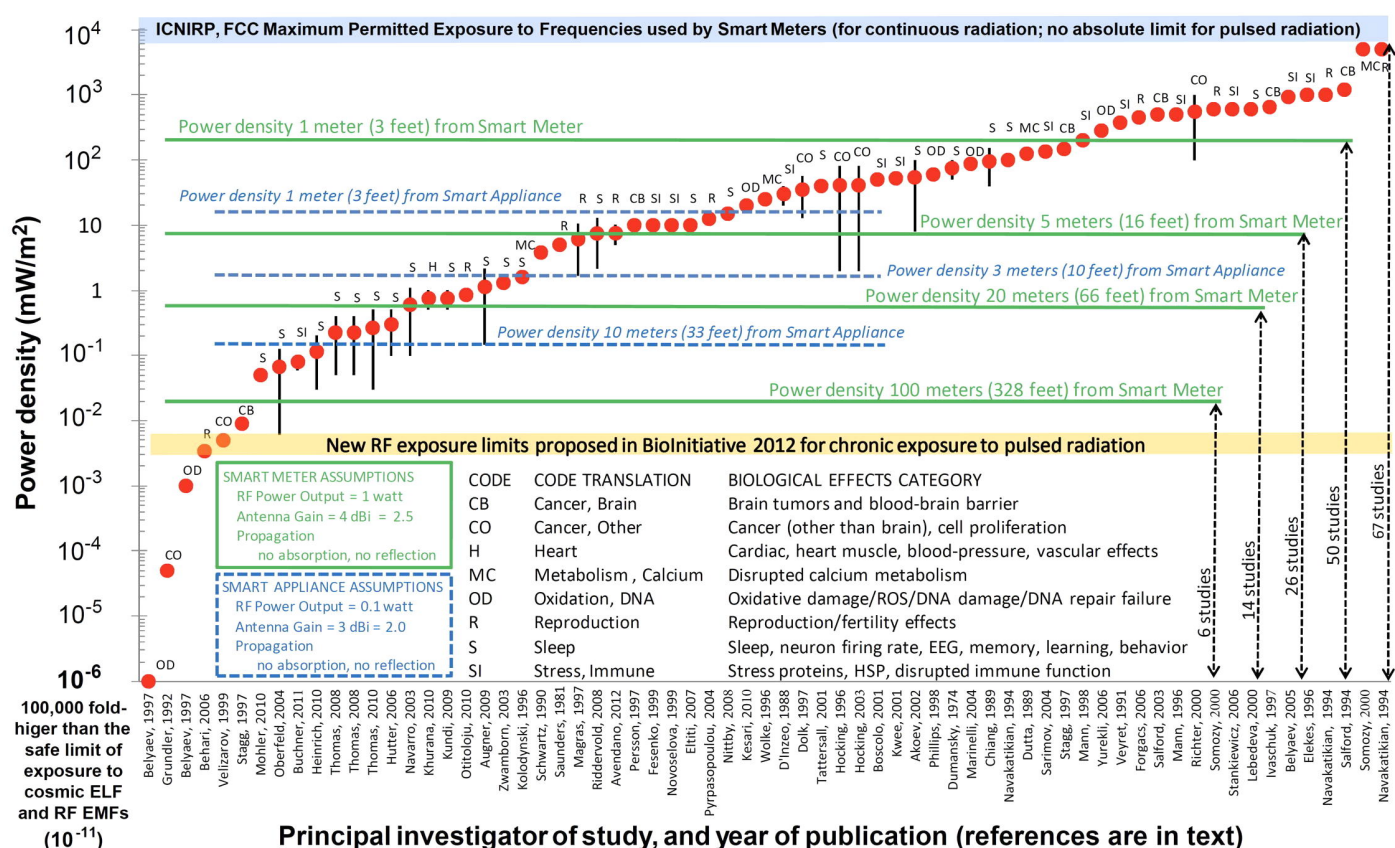
#### 4. Exposure Limits of Man-Made RF/ELF, EMF do Not Apply to Near-Fields: Biological Consequences

ICNIRP makes the following clarifications on the RF-EMF exposure limits about *near-fields*: “The situation in the *near-field* region is rather more complicated because the maxima and minima of  $E$  (electric) and  $H$  (magnetic) fields do not occur at the same points

along the direction of propagation as they do in the *far-field*. In the *near-field*, the electromagnetic field structure may be highly inhomogeneous, and there may be substantial variations from the plane wave impedance of 377 ohms; that is, there may be almost pure *E* fields in some regions and almost pure *H* fields in others. Therefore, exposures in the *near-field* are more difficult to specify because both *E* and *H* fields must be measured and because the field patterns are more complicated; in this situation, power density is no longer an appropriate quantity to use in expressing exposure restrictions (as in the *far-field*).” [76–78]. Additionally, ICNIRP notes that for the RF-EMF spectrum range of 5G, it is accepted that “Because the incident power density used for the reference levels above 6 GHz does not appropriately correlate with the absorbed power density used for the basic restrictions in the reactive near-field region, *reference levels* cannot be used to determine compliance in the reactive *near-field*” [11]. A culmination of the above statements is the conclusion by ICNIRP that the current exposure limits can be exceeded in RF/ELF EMF *near-fields* (e.g., emitted by electric appliances and cell phones): “*Near-field* exposure situations, localised and non-uniform field exposure, are of special interest. Typical EM sources with *near-field* exposure are hand-held mobile telephones, inductive or capacitive heating equipment, anti-theft devices or electric appliances in homes and workplaces. Such devices can emit localised fields *above the reference levels*.” [79]. Therefore, billions of individuals worldwide are overexposed daily by the RF-EMFs from their cell phones, tablets, laptops, etc.

The current man-made power density exposure limits are compared to nature’s limits, and some observed biological effects are shown in Figure 3. The biological effects are based on studies presented in the *BioInitiative 2012 Report* [34,80–139], which have been updated in the present study. Nonetheless, the number of such studies has grown since then, listing as indicative ones that focus on oxidative stress [2,44,53,54,106,128,140,141], DNA damage [54,142] and carcinogenesis [143–147].

Indeed, the lowest power density of  $1 \times 10^{-9} \text{ W/m}^2$  ( $1 \times 10^{-6} \text{ mW/m}^2$ ) with observed biological effects (oxidative damage, reactive oxygen species generation, DNA damage/repair failure) is  $\sim 10^{13}$ -fold higher than a natural exposure limit of  $\sim 1 \times 10^{-22} \text{ W/m}^2$  ( $10^{-19} \text{ mW/m}^2$ ) of exposure to the cosmic frequencies and  $10^{10}$ -fold lower than the today’s power density exposure limit of  $10 \text{ W/m}^2$  ( $1 \times 10^4 \text{ mW/m}^2$ ). Even the 3 to  $6 \times 10^{-6} \text{ W/m}^2$  (3 to  $6 \times 10^{-3} \text{ mW/m}^2$ ) limit proposed by the *BioInitiative 2012 Report* [148] is  $10^{14}$ – to  $10^{18}$ -fold higher than the natural exposure limit.



**Figure 3.** The biological effects of RF-EMF radiation with radiation power intensities lower of the International Commission on Non-Ionizing Radiation Protection/U.S. Federal Communications Commission (ICNIRP/FCC) exposure limit. The chart is a reference-updated and slightly modified from the original version [148].

## 5. Conclusions

This article follows a novel approach to reveal the main principles of the microwave interaction of natural and man-made radiation in resonance with biomatter. Quantum theory is applied to elucidate the effects of man-made microwave electromagnetic radiation on biological matter, in reference to the Earth's surface receiving cosmic radiation levels to which man's biology has been adapted. For this, the article extends its analysis to experimentally established quantum physics effects, such as microwave adiabatic tunnelling, the coherent interaction of microwaves with the rotational levels of water clusters, and the quantum properties of microwave interactions with water clusters.

The fact that the Sun's radiation reaching the Earth sets the actual natural exposure limits for man should bring into focus the sunlight-based VLC and OFC technologies, because VLC LEDs emit Sun-like photons that are also incoherent in terms of frequencies, waveforms, and phase difference [149,150], making them non biologically damaging. The latter is also supported by studies showing that VLC LEDs do not cause any damaging effects, even on the eye retina [150,151]. Moreover, VLCs, besides transmitting at speeds far above 5G, have been suggested as being capable of solving the significant challenges of 5G/IoT communication systems [152].

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