Science of the Total Environment 599–600 (2017) 2026–2034

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# On the biophysical mechanism of sensing atmospheric discharges by living organisms

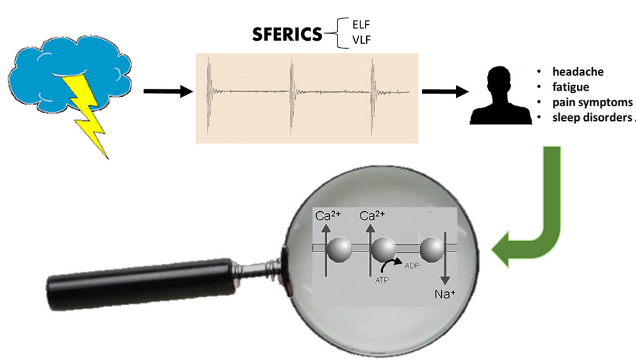
Dimitris J. Panagopoulos [a,b,c], Alfonso Balmori [d,*]

[a] National Center for Scientific Research "Demokritos", Athens, Greece
[b] Radiation and Environmental Biophysics Research Centre, Greece
[c] Department of Biology, University of Athens, Greece
[d] Consejería de Medio Ambiente, Junta de Castilla y León, C/Rigoberto Cortejoso, 14, 47071 Valladolid, Spain

## HIGHLIGHTS

- Atmospheric discharges - called sferics - can be sensed by living organisms.
- The symptoms are mainly headache, fatigue, sleep disorders etc.
- Sferics consist of partially polarized electromagnetic pulses.
- Sferics have adequate intensity and polarization to cause biological/health effects.
- We provide a novel biophysical explanation for sensing sferics by living organisms.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 2 March 2017
Received in revised form 10 May 2017
Accepted 10 May 2017
Available online xxxx

Editor: D. Barcelo

*Keywords:*
Atmospheric discharges
Sferics
Biological effects
Health effects
Mechanism of action
ELF
VLF
Schumann resonances

## ABSTRACT

Atmospheric electrical discharges during thunderstorms, and the related electromagnetic fields (EMFs)/waves called sferics, can be sensed by humans at long distances through a variety of symptoms, mainly headache, fatigue, etc. Up to today there is no explanation for this association. Sferics consist of partially polarized electromagnetic pulses with an oscillating carrier signal in the very low frequency (VLF) band and a pulse repetition frequency in the extremely low frequency (ELF) band. Their ELF intensity may reach ~5 mV/m at global ranges, and ~0.5 V/m at ~1000 km from the lightning. The health symptoms associated with sferics are also associated with antennas of mobile telephony base stations and handsets, which emit radio frequency (RF) radiation pulsed on ELF, and expose humans at similar or stronger electric field intensities with sferics. According to the Ion Forced-Oscillation mechanism, polarized ELF EMFs of intensities down to 0.1–1 mV/m are able to disrupt any living cell's electrochemical balance and function by irregular gating of electro-sensitive ion channels on the cell membranes, and thus initiate a variety of health symptoms, while VLF EMFs need to be thousands of times stronger in order to be able to initiate health effects. We examine EMFs from sferics in terms of their bioactivity on the basis of this mechanism. We introduce the hypothesis that stronger atmospheric discharges may reasonably be considered to be ~70% along a straight line, and thus the associated EMFs (sferics) ~70% polarized. We find that sferics mainly in the ELF band have adequate intensity and polarization to cause biological/health effects. We provide explanation for the effects of sferics on human/animal health on the basis of this mechanism.


* Corresponding author.
*E-mail address:* balmaral@jcyl.es (A. Balmori).

http://dx.doi.org/10.1016/j.scitotenv.2017.05.089

## 1. Introduction

One of the natural electromagnetic phenomena, associated with electromagnetic fields (EMFs)/electromagnetic radiation (EMR) with frequencies within the bands of the very low frequency (VLF) (3–30 kHz), and the extremely low frequency (ELF) (3–3000 Hz), is generated by thunderbolts and the lightning during thunderstorms. These natural EMFs/EMR are known to affect both the natural inanimate terrestrial environment and the living organisms. They consist of short-duration and dampened oscillating electromagnetic impulses of approximately sinusoidal shape, generated by the atmospheric discharges (lightning) (Barr et al., 2000; Tomko and Hepner, 2001; Schienle et al., 1998, 2001). Atmospheric discharges also simply called *atmospherics* or *sferics* occur due to the huge voltage differences developed by electric charge exchange between clouds, or between clouds and atmospheric particles, or between clouds and the Earth's surface (sea or ground). When the voltage difference becomes large enough, creating electric fields on the order of $\geq$10 kV/cm ($=10^6$ V/m),[1] and at the same time the atmospheric conductivity increases due to moisture before or during thunderstorms, the conditions are suitable for the formation of spark discharges which neutralize the strong electric fields by transferring electric charges to the opposite charged side of the developed field in the form of very sudden and intense electric currents on the order of tens of kA. The generated electromagnetic waves during the discharges are reflected by both the lower ionosphere and the Earth's surface propagating around the globe in a guided fashion between the Earth-ionosphere boundaries which form a natural waveguide (Francis, 1960; Nasser, 1970; Alexopoulos, 1973; Barr et al., 2000; Wood and Inan, 2004; Nagano et al., 2007; De et al., 2010; Inan et al., 2010). Due to this, they can be used to study the characteristics of lightning, as well as those of the lower ionosphere (Inan et al., 2010). From meteorological viewpoint, changes in the reception of electromagnetic waves from atmospheric discharges by proper receivers (antennas) are predictors of weather changes in a specific region when no other measurable signs (such as related changes in temperature, atmospheric pressure, humidity, etc.) are present (Vaitl et al., 2001a).

The continuous reflection of the global lightning electromagnetic waves within the Earth-ionosphere (quasi) spherical shell cavity creates an electromagnetic resonance which can be measured in the lower ELF band between 5 and 60 Hz. That was first discovered by Schumann (1952) and became known as the Schumann resonance effect. It was originally calculated that these resonances have a fundamental frequency at 10.6 Hz, with overtones at 18.4, 26.0, 33.5, and 41.1 Hz. A few years later Schumann's predictions were roughly confirmed experimentally by ELF noise spectra measurements and analysis and was found that these resonances have maxima at 7.8, 14.2, 19.6, 25.9, and 32.0 Hz (Balser and Wagner, 1960, 1963; Barr et al., 2000). The resonances were found to be a sensitive measure of temperature fluctuations in the tropical atmosphere, and consequently a measure of global climate change. A 2 °C change in temperature was found out to be able to create a 20-fold change in lightning activity (Williams, 1992). It is remarkable that the fundamental frequency of the electromagnetic atmospheric resonances is very close to the alpha rhythms of the electrical oscillations of the human brain (8–13 Hz) as recorded by electroencephalograms (EEG) (Schienle et al., 1997, 2001; Vaitl et al., 2001a, 2001b; Walach et al., 2001). Experiments conducted in the early 1960's with volunteers who spent several weeks in an underground bunker completely shielded electromagnetically, showed that when the natural electromagnetic atmospheric (Schumann) resonances were filtered out from the bunker, the individuals began feeling sick, experiencing headaches, emotional problems, stress and depression. By turning on an electric pulse generator producing an oscillating EMF with a frequency at 7.83 Hz, the problems retreated and disappeared (Wever, 1979).

During their propagation, sferics undergo attenuation with regard to their amplitude and changes in their frequency composition, especially in the VLF band, due to scattering/dispersion and dampening effects. The associated electric and magnetic field amplitudes diminish with distance from the thunderstorm area, especially in the VLF band, and due to the fact that different frequencies/wavelengths undergo different attenuations (see Eq. (1) below), the frequency composition of the sferics changes with the distance. As for their ELF components, these are significantly more penetrating than VLF, and can be more readily detected around the globe, constituting the "Schumann resonances" mentioned above (Schumann, 1952; Barr et al., 2000). The attenuation in the lower ELF band (3–60 Hz) is very small and amounts to only ~0.3 dB per 1000 km at 10 Hz, increasing with frequency to about 1 dB per 1000 km at 60 Hz (Barr et al., 2000).

The difference in attenuation with the distance between ELF and VLF electromagnetic waves is explained by the Rayleigh law which shows that the intensity of scattered EMR is inversely proportional to $\lambda^4$ (where $\lambda$ is the wavelength of EMR) when the dimensions of the scattering particles are smaller than the wavelength (Alexopoulos, 1966) (which is the case for sferics):

$$J_{\text{scat}} \propto \frac{1}{\lambda^4} \tag{1}$$

Besides their significance as indicators of thunderstorm activity, there is evidence that the electromagnetic impulses created by lightning can be sensed by animals including humans and are considered a possible trigger for changes in the somatic and emotional well-being of humans, referred to as weather sensitivity or meteoropathy (Höppe, 1997; Schienle et al., 1998; Walach et al., 2001; Martin et al., 2013). It has been suggested that the organisms' sensitivity to sferics may be the basis for weather sensitivity. In other words, it has been suggested that meteoropathy is actually a type of electro-hypersensitivity (EHS). It was observed that different patient groups displayed pain symptoms one or two days before an upcoming weather change when there were no visible signs for this change but the sferics activity had already increased (Reiter, 1960; Schienle et al., 1998). Despite the difficulties inherent in statistical/epidemiological studies based on questionnaires, the perception of weather changes by patients seems a reality hardly disputable (Becker, 2011; Yang et al., 2011).

In the present study we shall attempt to provide an explanation for the sensing of atmospheric discharges by living organisms on a biophysical/cellular basis.

### *1.1. Reported effects on human population*

For human subjects, positive correlations have been reported between the sferics activity (number of recorded lightning flashes per min and intensity of recorded impulses) and the occurrence of headache, pain symptoms, heart attacks, epileptic seizures, sleep disorders, errors made in a concentration task, and changes in the alpha and beta rhythms of the EEG, among others. These symptoms are recorded at long distances (thousands of km) from the thunderstorm area (Reiter, 1960; Laaber, 1987; Ludwig, 1973; Pelz and Swantes, 1986; Ruhenstroth-Bauer et al., 1984, 1985, 1987; Schienle et al., 1998, 2001; Martin et al., 2013).

It is reported that 30–78% of headache sufferers demonstrate sensitivity to weather changes, and more specifically to the intensity and number of atmospheric discharges ("flashes") detected per min. A statistically significant connection was verified (Walach et al., 2001). In another study, 54% of the German and 61% of the Canadian subjects reported that their health was affected by weather conditions (Von Mackensen et al., 2005). The most frequent symptoms caused by lightning on humans as reported in the same statistical study on German population, were headache/migraine (61%), lethargy (47%), sleep disturbances (46%), fatigue (42%), joint pain (40%), irritation (31%), depression (27%), vertigo (26%), concentration problems (26%) and scar pain (23%) (Von Mackensen et al., 2005). In another study, sferics

[1] The dielectric resistance of dry air is ~3 × $10^6$ V/m (Alexopoulos, 1973).

activity was significantly correlated with the occurrence of migraine-type headaches, and 59% of the women indicated that they suffered from headaches before a weather change (Vaitl et al., 2001a). In a more recent study the significant correlation of migraine-type headaches with lightning was verified again (Martin et al., 2013). Moreover artificially produced electromagnetic pulses of similar characteristics with those of atmospheric discharges (sferics) were found to affect the EEG of humans, especially the alpha (8–13 Hz) and beta (13–30 Hz) bands (Schienle et al., 1997, 2001; Vaitl et al., 2001a; Walach et al., 2001). Up to today, there is no physical/biological explanation for these biological/health effects caused by the sferics on human population (Schienle et al., 1998; Vaitl et al., 2001a; Walach et al., 2001).

It is most unfortunate though, that in all of the above studies, there was no attempt to specify whether the recorded health symptoms were correlated with the VLF carrier frequency or with the ELF pulse repletion frequency of the sferics (Fig. 1). In almost all of the above studies only the VLF carrier frequency was measured and there was no measurement of the ELF frequency or intensity of the detected sferics, and in the Martin et al. (2013) study there was no attempt to implicate the frequency of the associated EMFs at all. It seems that the ELF pulse repetition frequency was largely underestimated and only the VLF carrier frequency was actually noted. But according to the mechanism proposed below, it is the intensity of the ELF pulse repetition frequency of the sferics which is the most bioactive parameter, and much lesser the VLF.

It is noteworthy that similar symptoms with those above reported to be due to sferics, except for joint and scar pains, have been reported for populations residing close to mobile telephony base stations, and have been classified as "microwave syndrome" (Navarro et al., 2003; Salama and Abou El Naga, 2004; Hutter et al., 2006; Blettner et al., 2009; Kundi and Hutter, 2009; Viel et al., 2009; Singh et al., 2016). Moreover, it is well known that EMFs - especially in the ELF and RF bands - affect the human EEG, primarily the alpha and beta bands (Reiser et al., 1995; Huber et al., 2000, 2002; Krause et al., 2000, 2006; Croft et al., 2002, 2008; Curcio et al., 2005; Valentini et al., 2007; Regel et al., 2007; Roggeveen et al., 2015).

### 1.2. Characteristics of atmospheric discharges

It is estimated that about 2000 thunderstorms are taking place around the earth at any time creating about 100 lightning discharges per second (Orville and Spencer, 1979). The atmospheric lightning discharge is an electrical discharge creating a breakdown current flowing between cloud and ground (CG discharges), or between two different clouds (intra-cloud or IC discharges). CG discharges are more rare and usually more intense than IC, taking place on mountain tops, on high trees, tall buildings, but also on the sea surface due to the high conductivity of sea water.

The ratio of horizontal to the vertical component of atmospherics was found to be a function of the local conductivity of the earth surface and independent of source parameters (Divya and Rai, 1986). Later the same investigators measured these polarized components of electric fields at 5 kHz and from this obtained the value of soil conductivity (Divya and Rai, 1990).

A deeper look into the characteristics of lightning showed that CG lightning during thunderstorms is short duration discharges that contain electromagnetic impulses in the ELF range. More specifically, it was found that these ELF pulses have a carrier frequency in the VLF range (~10 kHz) (Fig. 1). The total lightning discharge - named a "flash" and lasting about 0.2 s - is comprised of several (1–30, but typically 4) pulses ('strokes') separated from one-another by about 50–60 ms intervals of approximately zero field/current (Fig. 1). Each pulse lasts for a few to tens of milli-seconds (typically 1–10 ms). The production of lightning lasts for an average duration of the thunderstorm ~10 min. The majority of lightning create ELF electric and magnetic fields on the order of 0.02–2 mV/m and ~3 pT respectively, as recorded at global ranges and constitute the "Schumann" background (Barr et al., 2000; De et al., 2010).

The 50–60 ms (=0.05–0.06 s) separation between successive individual pulses (strokes) within a single flash results in an ELF pulse repetition frequency of 17–20 Hz (Fig. 1). Nevertheless, lower values for the pulse repetition frequency (at the range 0–3 Hz) have been recorded as well (Schienle et al., 2001). We can reasonably consider that these CG discharges are more or less vertical to the ground and thus the produced ELF pulses are partially vertically polarized.

Distinguishable lightning events that exceed the global background - of root mean square (*rms*) amplitude ~1 mV/m or ~3 pT in the band 5–50 Hz - by a factor of three or more, occur at a rate of about one or two per minute having a duration of the total lightning discharge (flash) on the order of 0.5 s. The majority (~70%) of these distinguishably strong discharges are CG and produce large amplitude ELF sferics with a positive *E*-field polarity in regard to the ground. In other words, these distiguishble discharges lower positive charge to the Earth and they are assigned as +CG, in contrast to the majority of the ususal CG lightning discharges which are –CG and lower negative charge to Earth (Kemp, 1971; Huang et al., 1999; Barr et al., 2000). The fact that the majority of CG discharges lower negative charge to the Earth seems to be the reason for the development of the terrestrial static electric field - with an average intensity at zero height on the order of 130 V/m - in which the atmosphere is positively charged in regard to the ground (Watt, 1960; Presman, 1977).

At distances on the order of 100 km from a thunderstorm the electric and magnetic fields of recorded ELF sferics may reach values on the

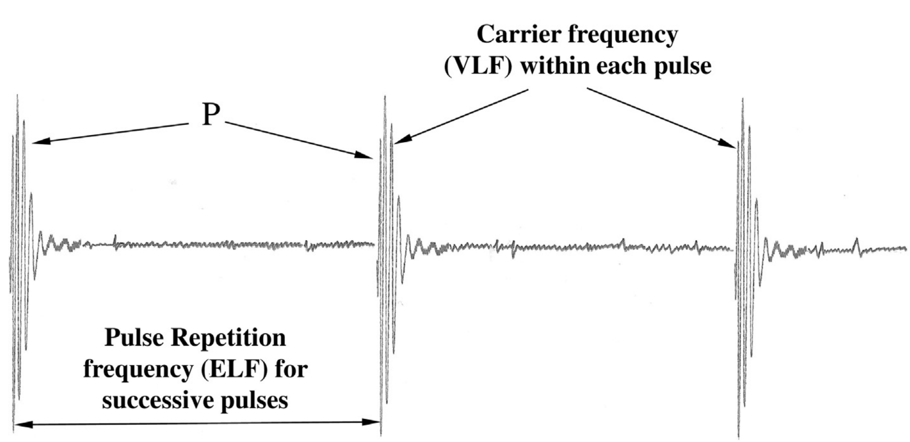



**Fig. 1.** Graphical representation of atmospheric discharge electric field/current ("flash") - in arbitrary scale - comprised of bipolar alternating damping pulses ("strokes") (P) with a VLF carrier, and a pulse repetition at the ELF band.

order of a few $(1-10)$ V/m and a few μT respectively, while at distances on the order of 1000 km the electric field reaches values around ~0.5 V/m decreasing linearly with the distance. At the same time, the electric field in the VLF band (around 5 kHz) reaches similar values (up to ~5 V/m at 100 km, and less than ~0.5 V/m at 1000 km distance) (Watt, 1960; Pathak et al., 1982; Reiter, 1995; Schienle et al., 1998).

The corresponding electromagnetic waves travel long distances with the velocity of light and with small attenuation, especially in the ELF band. Is it then possible that these partially polarized sferics can be sensed by living organisms thousands of km away from the thunderstorm? The answer seems to be absolutely positive as we shall explain below.

## 2. A crucial hypothesis on the polarization of Sferics

Electromagnetic waves produced by atmospheric discharges are long accepted to be predominantly vertically polarized (Stanford, 1971). Moreover, ELF sferics which are expected to be more bioactive than VLF - as we shall explain below - are mainly produced by CG lightning or the vertical component of IC lightning discharges. In other words, the ELF sferics are associated with vertically polarized electric fields and breakdown electric currents (Barr et al., 2000).

Thus, we are referring to ELF impulses at a frequency up to ~20 Hz, with an *rms* maximum intensity ~5 mV/m at global ranges, ~0.5 V/m at approximately 1000 km, and ~5 V/m at approximately 100 km, and with a vertical average orientation. This vertical average orientation of these ELF pulses makes them polarized in a significant degree (the produced electromagnetic waves can be considered plane waves with a partial vertical polarization).

In any case, each individual lightning has a specific average resultant direction in the sky and we may reasonably approximate it by a straight line of a specific direction. As each specific lightning may be postulated as partially having a specific direction, it follows that the produced electric and magnetic fields are polarized in a significant degree.

We can conservatively assume that the strong ("distinguishable") CG discharges are ~70% along a specific direction (vertical most usually), in other words we can postulate they are ~70% polarized. Thus, their totally polarized field strength is ~5 mV/m × 0.7 = ~3.5 mV/m at global ranges, ~0.5 V/m × 0.7 = ~0.35 V/m at 1000 km from thunderstorm, and ~5 V/m × 0.7 = ~3.5 V/m at 100 km. This hypothesis of polarization is crucially important for the mechanism of sensing the sferics by living organisms that we shall present below.

## 3. The sensing of sferics by living organisms according to the "ion forced-oscillation" mechanism

According to a published biophysical mechanism describing the action of weak polarized EMFs on living cells (Panagopoulos et al., 2000, 2002, 2015a), polarized ELF fields can easily alter the function of any living cell by irregular gating of electrosensitive cation channels on the cell membranes and consequent disruption of the cell's electrochemical balance, at very low field intensities on the order of ~1 mV/m. The mechanism predicts that the bioactivity of the field doubles for pulsed EMFs (such as those of the atmospheric discharges). This theoretical biophysical mechanism based on molecular data on voltage-gated cation channels and intracellular ionic oscillations, was verified for its plausibility by numerical test (Halgamuge and Abeyrathne, 2011). According to this theory, the forced-oscillation of ions in the vicinity of the voltage-sensors of voltage-gated ion channels induced by an externally applied EMF can exert forces on these sensors equal to or greater than the electrostatic forces - exerted by changes in the transmembrane electric field - known to physiologically gate these channels. Irregular gating of these channels can potentially disrupt any cell's electrochemical balance and function (Alberts et al., 1994), leading to a variety of biological/health effects including the most detrimental ones, such as DNA damage, cell death, or cancer (Pall, 2013).

A review of the whole EMF-bioeffects literature reveals that the most bioactive EMFs are the lower frequency ones, especially the ELF fields (Goodman et al., 1995). Moreover experimental data indicate that pulsed EMFs are more bioactive than continuous fields of the same rest characteristics (Goodman et al., 1995; Veyret et al., 1991; Penafiel et al., 1997). The pulse repetition frequency is always a low frequency, most usually ELF. As we already described, sferics are partially polarized, pulsed ELF fields that expose living organisms usually at intensities up to ~10 V/m (Barr et al., 2000).

All critical biomolecules are either electrically charged or polar (Alberts et al., 1994; Stryer, 1996). The sum electric field from an infinite number of individual electric pulses of random polarizations (as e.g. with natural light), tends to zero

$$\lim_{n\to\infty} \sum_{i=1}^{n} \vec{E}_i = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \ldots + \vec{E}_n = 0 \tag{2}$$

and thus, unpolarised EMFs at any intensity cannot induce any specific/coherent oscillation on these molecules (Panagopoulos et al., 2015a). On the contrary, polarized EMFs will induce a coherent and parallel forced-oscillation on every charged/polar molecule within biological tissue. This is fundamental to our understanding of the biological phenomena. Atmospheric discharges are polarized in a significant degree as explained, and thus able to induce such an oscillation on charged/polar biological molecules. This oscillation will be most evident on the free (mobile) ions which carry a net electric charge and exist in large concentrations in all types of cells or extracellular tissue determining practically all cellular/biological functions (Alberts et al., 1994). Although all molecules oscillate randomly in every direction with much higher velocities due to thermal motion, this has no biological effect other than increase in tissue temperature. But a coherent polarized oscillation of even millions of times smaller energy than average thermal molecular energy (Panagopoulos et al., 2013a) can initiate biological effects.

Most cation channels ($Ca^{+2}$, $K^{+}$, $Na^{+}$, etc.) on the membranes of all animal cells, are voltage-gated, or as they are usually called, "electrosensitive" (Alberts et al., 1994). They interconvert between open and closed state, when the electrostatic force on the electric charges of their voltage sensors due to transmembrane voltage changes, transcends some critical value. The voltage sensors of these channels are four symmetrically arranged, transmembrane, positively charged helical domains, each one designated S4. Changes in the transmembrane potential on the order of 30 mV are normally required to gate electrosensitive channels (Noda et al., 1986; Liman et al., 1991). Several ions may interact simultaneously each moment with an S4 domain from a distance on the order of 1 nm, since - except for the single ion that may be passing through the channel pore while the channel is opened - a few more ions are bound close to the pore of the channel at specific ion-binding sites (e.g. three in potassium channels) (Miller, 2000).

Consider e.g. four potassium ions at distances on the order of 1 nm from the channel-sensors (S4), and an externally applied oscillating EMF. The electric (and the magnetic) force on each ion due to any unpolarized EMF/EMR is zero (Eq. (2)). On the contrary, the force due to a polarized field with an electrical component $E$, is $F = Ezq_e$. It is shown that for a sinusoidal alternating field $E = E_o \sin\omega t$, the movement equation of a free ion of mass $m_i$, is (Panagopoulos et al., 2000, 2002):

$$m_\iota \frac{d^2r}{dt^2} + \beta\frac{dr}{dt} + m_\iota\ \omega_o{}^2 r = E_o z\ q_e\ \sin\omega\ t \tag{3}$$

where $r$ is the ion displacement due to the forced-oscillation, $z$ is the ion's valence ($z = 1$ for potassium ions), $q_e = 1.6 \times 10^{-19}$ C the elementary charge, $\beta$ the damping coefficient for the ion displacement (calculated to have a value within a channel $\beta \cong 6.4 \times 10^{-12}$ kg/s), $\omega_o = 2\pi\nu_o$ ($\nu_o$ the ion's oscillation self-frequency taken equal to the ion's recorded spontaneous intracellular oscillation frequency on the order of 0.1 Hz), $\omega = 2\pi\nu$ ($\nu$ the frequency of the field/radiation), and $E_o$ the amplitude of the field.

The general solution of Eq. (3), is:

$$r = \frac{E_o z q_e}{\beta\omega} \cos\omega t + \frac{E_o z q_e}{\beta\omega} \tag{4}$$

The term $\frac{E_o z q_e}{\beta\omega}$ in the solution, represents a constant displacement, but has no effect on the oscillating term $\frac{E_o z q_e}{\beta\omega} \cos\omega t$. This constant displacement doubles the amplitude $\frac{E_o z q_e}{\beta\omega}$ of the forced-oscillation at the moment when the field is applied or interrupted, or during its first and last periods, and the ion's displacement will be twice the amplitude of the forced-oscillation. For pulsed fields (such as those associated with atmospheric discharges, or the fields of modern digital telecommunications) this will be taking place constantly with every repeated pulse. Thus, pulsed fields are - theoretically - twice more drastic (bioactive) than continuous/non-interrupted fields of the same other parameters, in agreement with several experimental data (Goodman et al., 1995; Veyret et al., 1991; Penafiel et al., 1997).

The amplitude of the forced-oscillation (ignoring the constant term in Eq. (4)), is:

$$A = \frac{E_o z q_e}{\beta\omega} \tag{5}$$

The force acting on the effective charge $q$ of an S4 domain, via an oscillating single-valence free cation, is: $F = \frac{1}{4\pi\varepsilon\varepsilon_o} \cdot \frac{q \cdot q_e}{r^2}$, ($r$ is the distance of the free ion from the effective charge of S4). Each oscillating cation displaced by $dr$, induces an additional force on each S4 sensor, due to its displacement:

$$dF = -\frac{q \cdot q_e}{2\pi\varepsilon\varepsilon_o r^3} dr \tag{6}$$

While in the case of a non-polarized applied field $\sum d\vec{r} = 0$, and $\sum d\vec{F} = 0$, in the case of a polarized applied field (or significantly polarized such as those of CG sferics), the sum force on the channel sensor from all four cations, is:

$$4dF = -2\frac{q \cdot q_e}{\pi\varepsilon\varepsilon_o r^3} dr$$

The effective charge of each S4 domain is found to be: $q = 1.7\ q_e$ (Liman et al., 1991). The minimum force on this charge required normally to gate the channel - equal to the force generated by a change of 30 mV in the membrane potential (Liman et al., 1991) - is calculated (Panagopoulos et al., 2000) and found to be:

$$dF = 8.16 \times 10^{-13}\ \text{N}.$$

The displacement of one single-valence cation within the channel, necessary to exert this minimum force is then calculated from Eq. (6) to be:

$$dr = 4 \times 10^{-12}\ \text{m}$$

For 4 cations oscillating in phase and on parallel planes due to an external polarized field, the minimum displacement is decreased to: $dr = 10^{-12}$ m.

Therefore, any external polarized oscillating EMF able to force free ions to oscillate with amplitude $\frac{E_o z q_e}{\beta\omega} \geq 10^{-12}$ m, is able to irregularly gate cation channels on cell membranes. For $z = 1$ (potassium ions), and substituting the values for $q_e$, $\beta$ on the last condition, we get:

$$E_o \geq 0.25\nu \times 10^{-3} \quad (\nu \text{ in Hz}, E_o \text{ in V/m}) \tag{7}$$

For double-valence cations ($z = 2$) (e.g. $Ca^{+2}$) the condition becomes,

$$E_o \geq \nu \times 10^{-4} \quad (\nu \text{ in Hz}, E_o \text{ in V/m}) \tag{8}$$

For pulsed fields (such as those associated with sferics) the second part of Condition 8 is divided by 2, and becomes:

$$E_o \geq 0.5\nu \times 10^{-4} \quad (\nu \text{ in Hz}, E_o \text{ in V/m}) \tag{9}$$

For atmospheric fields producing ELF pulses with a pulse repetition frequency $\nu = 20$ Hz (conservatively taking the highest one) (Barr et al., 2000), Condition 9 becomes:

$$E_o \geq 0.001\ \text{V/m}\ (= 1\ \text{mV/m}) \tag{10}$$

For 2 Hz sferic EMFs that have been recorded (Schienle et al., 2001):

$$E_o \geq 0.0001\ \text{V/m}\ (= 0.1\ \text{mV/m}) \tag{11}$$

Thus, polarized and pulsed ELF electric fields generated during thunderstorms stronger than 0.1–1 mV/m are potentially able to disrupt the function of any living cell.

The maximum ELF intensity for totally polarized atmospheric discharges at global ranges (many thousands of kilometers away from the location of a thunderstorm) was calculated above to be ~3.5 mV/m, and thus the bioactivity conditions 10, 11 are satisfied both for the lowest (2 Hz) and highest (20 Hz) ELF sferic frequencies.

For $N$ number of parallel sferics reaching simultaneously at certain locations of constructive interference, the last value may be divided by $N$ (Panagopoulos et al., 2015a).

Thus, the value of 3.5 mV/m totally polarized electric field intensity calculated above for the stronger CG discharges at global ranges, and even more the values of 0.35 V/m at 1000 km and 3.5 V/m at 100 km, are certainly able to induce irregular gating of electrosensitive ion channels on animal cell membranes and thus be sensed by sensitive individuals.

For 10 kHz VLF sferics EMFs, Condition (9) gives: $E_o \geq 0.5$ V/m. Strong VLF sferics may posses such intensities for distances up to ~1000 km from a thunderstorm as mentioned above.

It becomes clear that the amplitude of the ions' forced-oscillation given by Eq. (5) is the final parameter to quantitatively estimate the ability of an externally applied polarized EMF to induce biological/health effects. We shall call this amplitude, "Bioactivity of the EMF". Thus:

$$\text{EMF-Bioactivity} = \frac{E_o z q_e}{\beta\omega} = \text{k}\ \frac{E_o}{\nu} \tag{12}$$

where $k = \frac{z q_e}{2\pi\beta}$ is a constant quantity for any specific ion type in the vicinity of a voltage-gated ion channel in a cell membrane, $E_o$ the amplitude and $\nu$ the frequency of the applied electric field.

Eq. (12) shows that the biological activity of an oscillating EMF is proportional to the field's maximum intensity (amplitude) ($E_o$) and inversely proportional to the field's frequency ($\nu$). Thus, lower frequency fields are more bioactive than higher frequency ones with the same other parameters. This refers to all types of polarized harmonically oscillating EMFs. Non-harmonically oscillating EMFs may also be approximately described in terms of their bioactivity by Eq. (12).

For pulsed EMFs with harmonically oscillating pulses, the bioactivity equation doubles:

$$\text{Pulsed-EMF-Bioactivity} = 2k\,\frac{E_o}{\nu} \tag{13}$$

We do not distinguish between externally applied EMFs and internally induced ones within living tissue, especially in the case of ELF for the following reasons: 1. Living tissue is not metal to shield from electric fields and certainly is not ferromagnetic metal (Fe, Co, Ni) to shield from magnetic fields. Moreover, it is known that especially ELF fields cannot be easily shielded even by Faraday cages and in order to significantly minimize them it is recommended to totally enclose them in closed metal boxes (Panagopoulos et al., 2015a). Even sea water which has a considerably higher conductivity than living tissue is penetrated by ELF electromagnetic waves up to certain depths allowing in this way communication with submarines (Barr et al., 2000). Thus, ELF electric fields penetrate living tissue with certain degree of attenuation, and magnetic fields penetrate with zero attenuation. 2. Even in case that the ELF fields were significantly attenuated in the inner tissues of a living body, the eyes, the brain, the skin cells, or the myriads of nerve fiber terminals that end up on the outer epidermis, are directly exposed to the field intensities measured externally on the surface of the living tissue.

Moreover, it has been shown that tissue preparations (such as bovine fibroblasts or chicken tendons) respond to externally applied pulsed or sinusoidal ELF electric fields (by changes in DNA or protein synthesis rates, proliferation rates, alignment with respect to the field direction, etc.), at very low thresholds ~$10^{-3}$ V/m (Goodman et al., 1995; McLeod et al., 1987; Cleary et al., 1988; Lee et al., 1993). These thresholds are very close to those predicted above by the described mechanism.

Except for direct electric field exposure by an external field, there can be an electric field within tissues induced by an externally applied oscillating magnetic one, which - as explained - penetrates living tissue with zero attenuation.

Thus, we have shown that - according to the presented "Ion Forced-Oscillation Mechanism" - the ELF EMFs associated with atmospheric discharges (lightning) at global rages and the VLF fields at distances up to ~1000 km, are strong enough to affect any living cell's electrochemical balance and function, and consequently be sensed by living organisms.

At distances around ~100 km, the intensities of associated ELF and VLF sferics are both on the order of ~5 V/m, and the ratio of ELF Bioactivity versus VLF Bioactivity of sferics as it comes by applying Eq. (13), substituting $E_{o\ ELF} = 5$ V/m, $\nu_{ELF} = 10$ Hz, and $E_{oVLF} = 5$ V/m, $\nu_{VLF} = 10$ kHz, is:

$$(\text{ELF}/\text{VLF})\ \text{Bioactivity} = \frac{E_{oELF}\cdot\nu_{VLF}}{E_{oVLF}\cdot\nu_{ELF}} \cong 10^3 \tag{14}$$

Thus, the bioactivity of ELF sferics at 100 km from a thunderstorm is about 1000 times greater than the bioactivity of VLF sferics at the same distance. For longer distances the ratio becomes even larger, as the VLF components attenuate considerably faster than ELF.

## 4. Discussion

In the present study we provided for the first time a plausible explanation on a biophysical basis for the effect of sensing atmospheric discharges by living organisms, and more specifically by humans. We showed that strong CG atmospheric electrical discharges considered vertical to the ground - or in any case straight (polarized) at ~70% degree - are associated with ELF electric fields (frequency 0–20 Hz) with intensity up to ~5 V/m (or ~3.5 V/m totally polarized) at 100 km, and up to ~0.5 V/m (or ~0.35 V/m totally polarized) at 1000 km distance from a thunderstorm. According to the "Ion Forced-Oscillation Mechanism" for the action of weak, polarized ELF EMFs on cells (Panagopoulos et al., 2000, 2002, 2015a), such fields can potentially disrupt any living cell's electrochemical balance causing cellular stress and thus they can be sensed by living organisms/humans through a variety of symptoms such as headache, fatigue, etc. This is already confirmed by many statistical studies on human population as well by clinical studies showing effects of simulated electric pulses similar to those associated with atmospheric discharges (sferics) on human EEG (Schienle et al., 1997; Vaitl et al., 2001a; Walach et al., 2001; Von Mackensen et al., 2005; Martin et al., 2013). Artificially produced electromagnetic pulses of similar characteristics with natural sferics and employed in experimental clinical studies are totally polarized and thus even more bioactive than natural sferics.

Thus according to our present study, the sensing of upcoming thunderstorms by humans/animals through a variety of somatic/emotional symptoms is not anymore a strange or unexplained phenomenon, but it is actually a type of EHS.

The Ion Forced-Oscillation theory and its bioactivity Eq (13) (and Eq. (14)) imply that the effects of sferics on human/animal health are mainly due to the ELF components of the sferics (pulse repetition frequency). According to the bioactivity Eq. (13), a 10 kHz (VLF) field is ~$10^3$ times less bioactive than a 10 Hz (ELF) field of the same intensity $E_o$ and other parameters. While a 10 Hz field can be bioactive at very small intensities down to $E_o \geq 0.5$–1 mV/m, a 10 kHz field will be bioactive for intensities $E_o \geq 0.5$ V/m. Such VLF intensities are accounted at distances up to ~1000 km from the lightning source (Pathak et al., 1982). Thus, in locations closer to the thunderstorm area where the VLF components of the sferics are of this order of magnitude (≥0.5 V/m), the reported biological effects can literally be due to both the VLF and ELF sferic components, but actually it is about a thousand times more likely that the effects are due to the ELF. The frequency of the sferics that will eventually affect the organism (ELF or VLF) should not necessarily have an effect on the quality of the symptoms. Polarized EMFs of different frequencies will all cause irregular channel gating of electrosensitive ion channels on animal cell membranes once they have adequate (different) intensities.

Thus, we showed that ELF sferics can be sensed by animals around the glob, while VLF sferics can be sensed at distances up to ~1000 km from a thunderstorm, but even at such distances any recorded biological/health effects are far more likely (~1000 times) to be due to the ELF than to the VLF sferics produced by this particular thunderstorm.

Simultaneous atmospheric discharges of similar polarization and other characteristics can even create phenomena of momentary constructive interference at certain locations where living organisms will be exposed momentarily to even stronger field intensities than from single discharges (Panagopoulos et al., 2015a).

Natural EMFs in the terrestrial environment are never totally polarized in contrast to all man-made EMFs, but when they are polarized in a significant degree and at the same time significantly varying in their intensities and their other parameters, they can be sensed by living organisms through biological alterations associated with disruption of electrochemical cellular balance as described by the Ion Forced-Oscillation Mechanism. Terrestrial electric and magnetic fields are static and significantly polarized but normally with small variations in their intensities. Living organisms are adapted to these natural invariant fields for billions of years throughout Evolution. But during larger variations on the order of ±20% of their normal intensities, occurring every ~11 years and lasting for a few weeks due to variations in solar activity called magnetic storms, significant health implications in human/animal populations take place (Dubrov, 1978; Presman, 1977; Panagopoulos et al., 2015b). In a very similar way, voltage-gated (electrosensitive) cation channels in all animal cell-membranes do not alter their status (open or closed) while the electric field of the membrane (static and significantly polarized) keeps its normal value (~100 mV) (Alberts et al., 1994). But when changes on the order of 30 mV occur, the generated electrostatic forces on the channels' voltage sensors are adequate to alter the condition of the channel (Liman et al., 1991; Panagopoulos et al., 2000). Similarly, living organisms on Earth are adapted to the natural EMFs of atmospheric discharges. For this reason most organisms do not have stress symptoms against such fields at usual intensities. On the contrary, these fields seem to be vital for the function of their biological clock. The unpleasant symptoms are expected to be experienced by EHS individuals during intense thunderstorms creating the strongest and more polarized CG discharges referred to above. Moreover, humans in general may be more sensitive than other animals/organisms, as they have become more delicate, especially in modern urban environments. The sensing patterns against sferics may be different in different species, and similarly the symptoms against any type of externally induced cellular stress. Certainly, man-made highly variable and totally polarized EMFs are expected to be significantly more bioactive than the most bioactive (partially polarized) natural ones.

Except for the mechanism of sensing atmospheric discharges by living organisms (including humans) described in the present study, it is important to note that the natural ELF atmospheric electromagnetic resonances due to global lightning activity (also referred to as Schumann resonances) have their basic frequencies very close to the alpha-rhythm of the human brain electrical oscillations. Thus, it seems that the ELF frequencies of the atmospheric electrical discharges operate as a stimulus for the human/animal brain electrical activity and thus they constitute a very significant part of the animals' biological clock in addition to the diurnal light-dark cycle in the terrestrial environment (Panagopoulos, 2013). This is in complete agreement with the Wever (1979) experiments that we referred to in the Introduction. Moreover, remarkable similarities of analogue characteristics between sferic EMFs and axonal action potentials in animal brain nerve cells have been reported (Persinger, 2012).

Specific cells in specific sensory organs of all animals, different for a variety of external (or internal to the animal body) physical factors (electromagnetic stimuli, chemical stimuli, mechanical pressure, etc.), are responsible for the reception and adaptation by the organism in response to each different factor. The ion channels on the cells' plasma membranes play a very important role on that. On the plasma membranes of all animal cells there are ion channels sensitive to a variety of external factors (lingant-gated channels sensitive to chemical factors, mechanically-gated channels sensitive to pressure, and voltage-gated channels sensitive to electromagnetic signals are the most important classes of ion channels) (Stryer, 1996). The percentage of each type of ion channel on a specific cell depends upon the specificity of the cell and the organ of which the cell is part of. The voltage-gated channels which are primarily cation channels on the cells' plasma membranes of all animals are thus expected to play a major role on the sensing of sferics and on conveying the information of the Schumann resonances necessary for the function of the animal's biological clock.

Electromagnetic sensitivity to sferics might be an important factor in some headache patients and especially for so called "weather sensitive patients" (Walach et al., 2001). Weather sensitivity and the incidence of symptoms or exacerbation of diseases related to weather changes is known as impairment on well-being (Von Mackensen et al., 2005). This, apart from the effects on health and well-being, can have important socio-economic consequences. Subjects who had scored high on weather sensitivity symptoms and reported significantly greater pain intensity and duration, displayed prolonged EEG changes due to simulated sferics exposure and perceived the exposure as more exhausting and emotionally distressing (Schienle et al., 2001).

Walach et al. (2001) proposed that it may be of clinical importance that some headache patients could be sensitive to electromagnetic radiation emitted by various electric devices as mobile phones and others. This is in complete agreement with our remark in the Introduction of the present study, that similar symptoms except for joint and scar pains have been reported for populations residing close to mobile telephony base stations, and have been classified as "microwave syndrome" (Navarro et al. 2003; Salama and Abou El Naga, 2004; Hutter et al., 2006; Blettner et al., 2009; Kundi and Hutter, 2009; Viel et al., 2009; Singh et al., 2016). Moreover, Walach et al. (2001) hypothesis is also in complete agreement with the fact that EMFs - especially in the ELF and RF (pulsed on ELF) bands - affect the human EEG, primarily the alpha and beta bands (Reiser et al., 1995; Huber et al., 2000, 2002; Krause et al., 2000, 2006; Croft et al., 2002, 2008; Kramarenko and Tan, 2003; Curcio et al., 2005; Valentini et al., 2007; Regel et al., 2007; Roggeveen et al., 2015). Some investigators suggest that the increase in electromagnetic pollution in recent years is the cause of a real epidemic of electro-sensitive (EHS) people worldwide (Hallberg and Oberfeld, 2006). Our present study shows that the sensing of sferics through a variety of described symptoms by humans is actually a type of electro-hypersensitivity.

Thus, the reported association between headache and weather, and the fact that headache sufferers frequently describe weather changes as triggers (Becker, 2011; Yang et al., 2011), is now plausibly explained by our present study. Weather patterns reflect a complex interaction among multiple meteorological factors. For this reason it is difficult to analyze them and until now conventional methods have not shown to be adequate to investigate this. Yang et al. (2011) analysed separately the temporal relationship between headache and individual weather variables (pressure, humidity, temperature, wind speed etc.) during warm and cold periods with a novel statistical system (Method of Empirical Mode Decomposition: EMD) and they found that the cold fronts show the highest correlations with symptoms. Precisely cold fronts are associated with severe storms and therefore with stronger sferics (Vaitl et al., 2001b). Thus, according to our present study, it is expected that cold fronts may have a stronger correlation with health symptoms.

In our present study we make the point that the bioactive factor of the atmospheric discharges is mainly their ELF pulse repetition frequency, and secondarily the VLF pulse carrier frequency. Older studies have connected a-priori the bioactivity of sferics with their VLF frequency, although in those studies both VLF and ELF components were present and there was no attempt to study separately those components and find out which one is really the bioactive one (Jacobi et al., 1981; Schienle et al., 1998). Although there are several studies that have recorded effects on human EEG (especially on the alpha rhythm) only by ELF stimulation (without VLF) (Lyskov et al., 1993; Schienle et al., 1998; Cook et al., 2004; Marino et al., 2004; Ghione et al., 2005), we found no studies that have recorded similar effects by VLF exposure alone (without the co-existence of ELF). These data further verify our conclusions. Moreover, plenty of data indicate a variety of biological effects caused by ELF EMFs (Marino and Becker, 1977; McLeod et al., 1987; Cleary et al., 1988; Polk, 1991; Lee et al., 1993; Goodman et al., 1995; Stavroulakis, 2003; Panagopoulos et al., 2013b).

The results of our present theoretical research should be tested experimentally, especially by colleagues specialized on experimental techniques with simulated sferics. In order to verify whether indeed ELF are more bioactive than VLF we suggest they should compare the effects on EEG and on subjective symptoms between a continuous VLF signal (without ELF pulses), and a VLF signal of the same intensity and frequency pulsed on ELF. Then compare both these signals with an ELF-alone signal comprised of single monopolar pulses repeated on ELF frequency.

In any case, it seems that there is an increased sensitivity of living organisms to ELF EMFs. That was pointed out earlier by other investigators who had attributed this increased bioactivity of the ELF on the fact that living organisms were exposed at the beginning of biological evolution on Earth to intense thunderstorm activity and therefore, to stronger sferics and associated ELF fields (König et al., 1981; Schienle et al., 1998). According to our present study, such speculations are not anymore necessary. The increased animal sensitivity to ELF EMFs is simply explained by the physics and biology of the voltage-gated cation channels in all animal cell membranes and the increased ability of the ELF fields to irregularly gate these channels disrupting in this way the electrochemical balance of the cells/organisms, as explained by the Ion Forced-Oscillation theory.

In the present study we showed theoretically that partially polarized ELF EMFs from sferics can be sensed by EHS individuals through a variety of mild unpleasant health symptoms. It follows that the totally polarized man-made EMFs which almost always include ELF components (power line 50–60 Hz fields, digital wireless communications RF fields always pulsed on ELF, etc.) exposing people usually at significantly stronger intensities than sferics (up to ~20 V/m ELF pulses from mobile phones at close proximity to the body/head or up to ~10 kV/m close to power lines or transformers), may be significantly more bioactive inducing unpleasant health symptoms at significantly higher degrees, especially to EHS individuals (Panagopoulos et al., 2010, 2013b).

In our present study we provided a novel biophysical explanation of sensing atmospheric discharges (sferics) by living organisms including humans. We do hope that our present work will initiate more research on this topic which is of great importance for the well-being of a large portion of the human population worldwide.

## Declaration

The authors declare they have no actual or potential competing financial interests.

## References

Alberts, B., et al., 1994. Molecular Biology of the Cell. Garland Publishing, Inc., N.Y., USA.
Alexopoulos, C.D., 1966. Optics, Athens. (Αλεξόπουλος ΚΔ, Οπτική, Αθήνα 1966, Εκδόσεις Παπαζήση).
Alexopoulos, C.D., 1973. Electricity, Athens. (Αλεξόπουλος ΚΔ, Ηλεκτρισμός, Αθήνα 1973, Εκδόσεις Παπαζήση).
Balser, M., Wagner, C.A., 1960. Observations of Earth-ionosphere cavity resonances. Nature 188, 638–641.
Balser, M., Wagner, C.A., 1963. E_ect of a high altitude nuclear detonation on the Earth-ionosphere cavity. J. Geophys. Res. 68, 4115–4118.
Barr, R., Llanwyn, Jones D., Rodger, C.J., 2000. ELF and VLF radio waves. J. Atmos. Sol. Terr. Phys. 62, 1689–1718.
Becker, W.J., 2011. Weather and migraine: can so many patients be wrong? Cephalalgia 31 (4), 387–390.
Blettner, M., Schlehofer, B., Breckenkamp, J., Kowall, B., Schmiedel, S., Reis, U., Potthoff, P., Schuz, J., Berg-Beckhoff, G., 2009. Mobile phone base stations and adverse health effects: phase 1 of a population-based, cross-sectional study in Germany. Occup. Environ. Med. 66, 118–123.
Cleary, S.F., Liu, L.M., Graham, R., Diegelmann, R.F., 1988. Modulation of tendon fibroplasia by exogenous electric currents. Bioelectromagnetics 9, 183–194.
Cook, C.M., Thomas, A.W., Prato, F.S., 2004. Resting EEG is affected by exposure to a pulsed ELF magnetic field. Bioelectromagnetics 25, 196–203.
Croft, R.J., Chandler, J.S., Burgess, A.P., Barry, R.J., Williams, J.D., Clarke, A.R., 2002. Acute mobile phone operation affects neural function in humans. Clin. Neurophysiol. 113, 1623–1632.
Croft, R., Hamblin, D., Spong, J., Wood, A., McKenzie, R., Stough, C., 2008. The effect of mobile phone electromagnetic fields on the alpha rhythm of human electroencephalogram. Bioelectromagnetics 29, 1–10.
Curcio, G., Ferrara, M., Moroni, F., D'inzeo, G., Bertini, M., De Gennaro, L., 2005. Is the brain influenced by a phone call?: an EEG study of resting wakefulness. Neurosci. Res. 53, 265–270.
De, S.S., De, B.K., Bandyopadhyay, B., Guha, G., Paul, S., Bhowmick, A., Haldar, D.K., Chattopadhyay, G., Sanfui, M., 2010. Studies on the variations of ELF atmospherics over Kolkata. Bulg. J. Phys. 37, 37–47.
Divya, Rai, J., 1986. Calculation of electric fields from lightning above finitely conducting ground. Indian J. Radio Space Phys. 15, 96.
Divya, Rai, J., 1990. A new technique of measuring ground conductivity at VLF using atmospherics. J. Instrum. Soc. India 20, 143.
Dubrov, A.P., 1978. The Geomagnetic Field and Life. Plenum Press, New York.
Francis, G., 1960. Ionization Phenomena in Gases. Butterworths Scientific Publications, London.
Ghione, S., Seppia, C.D., Mezzasalma, L., et al., 2005. Effects of 50 Hz electromagnetic fields on electroencephalographic alpha activity, dental pain threshold and cardiovascular parameters in humans. Neurosci. Lett. 382, 112–117.
Goodman, E.M., Greenebaum, B., Marron, M.T., 1995. Effects of electro- magnetic fields on molecules and cells. Int. Rev. Cytol. 158, 279–338.
Halgamuge, M.N., Abeyrathne, C.D., 2011. A study of charged particle's behavior in a biological cell exposed to AC-DC electromagnetic fields. Environ. Eng. Sci. 28, 1–10.
Hallberg, Ö., Oberfeld, G., 2006. Letter to the editor: will we all become electrosensitive? Electromagn. Biol. Med. 25, 189–191.
Höppe, P., 1997. Aspects of human biometerology in past, present and future. Int. J. Biometeorol. 40 (1), 19–23.
Huang, E., Williams, E., Boldi, R., Heckman, S., Lyons, W., Taylor, M., Nelson, T., Wong, C., 1999. Criteria for sprites and elves based on Schumann resonance observations. J. Geophys. Res. 104 (16), 943–16,964.
Huber, R., Graf, T., Cote, K.A., Wittmann, L., Gallmann, E., Matter, D., Schuderer, J., Kuster, N., Borbély, A.A., Achermann, P., 2000. Exposure to pulsed high-frequency electromagnetic field during waking affects human sleep EEG. Neuroreport 11 (15), 3321–3325.
Huber, R., Treyer, V., Borbely, A., Schuderer, J., Gottselig, J., Landolt, H.P., et al., 2002. Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. J. Sleep Res. 11, 289–295.
Hutter, H.-P., Moshammer, H., Wallner, P., Kundi, M., 2006. Subjective symptoms, sleeping problems, and cognitive performance in subjects living near mobile phone base stations. Occup. Environ. Med. 63, 307–313.
Jacobi, E., Richter, O., Krüskemper, G., 1981. Simulated VLF-fields as a risk factor of thrombosis. Int. J. Biometeorol. 25, 133.
Inan, U.S., Cummer, S.A., Marshall, R.A., 2010. A survey of ELF and VLF research on lightning-ionosphere interactions and causative discharges. J. Geophys. Res. 115, A00E36. http://dx.doi.org/10.1029/2009JA014775.
Kemp, D.T., 1971. The global location of large lightning discharge from single station observations of ELF disturbances on the Earth-ionosphere cavity. J. Atmos. Terr. Phys. 33, 919–927.
König, H.L., Krueger, A.P., Lang, S., Sönning, W., 1981. Biological Effects of Environmental Electromagnetism. Springer-Verlag, New York.
Kramarenko, A.V., Tan, U., 2003. Effects of high frequency electromagnetic fields on human EEG: a brain mapping study. Int. J. Neurosci. 113, 1007–1019.
Krause, C.M., Sillanmäki, L., Koivisto, M., Häggqvist, A., Saarela, C., Revonsuo, A., Laine, M., Hämäläinen, H., 2000. Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task. Int. J. Radiat. Biol. 76 (12), 1659–1667.
Krause, C.M., Björnberg, C.H., Pesonen, M., Hulten, A., Liesivuori, T., Koivisto, M., Revonsuo, A., Laine, M., Hämäläinen, H., 2006. Mobile phone effects on children's event-related oscillatory EEG during an auditory memory task. Int. J. Radiat. Biol. 82 (6), 443–450.
Kundi, M., Hutter, H.P., 2009. Mobile phone base stations – effects on wellbeing and health. Pathophysiology 16, 123–135.
Laaber, M., 1987. Einp.P verschiedener Linweltparameter auf das Aufmerksamkeits Konzentrationsverhalten von Schulkindern unter besonderer Beachtung der Sferics (Influence of different environmental parameters on attention/concentration of pupils focusing of sferics). (Doctoral Thesis). University of Vienna, Austria.
Lee, R.C., Canaday, D.J., Doong, H., 1993. A review of the biophysical basis for the clinical application of electric fields in soft-tissue repair. J. Burn Care Rehabil. 14, 319–335.
Liman, E.R., Hess, P., Weaver, F., Koren, G., 1991. Voltage-sensing residues in the S4 region of a mammalian $K^+$ channel. Nature 353, 752–756.
Ludwig, H.W., 1973. Wirkungen einer nachtlichen Abschirmung der elektrischen Feldstarke bei Rheumatikern (Effects of nightly shielding of electric field strength on rheumatic patients). Arch. Meteorol. Geophys. Bioklimatol. A 21, 305–311.
Lyskov, E., Juutilainen, J., Jousmaki, V., Hänninen, O., Medvedev, S., Partanen, J., 1993. Influence of short-term exposure of magnetic field on the bioelectric processes of the brain and performance. Int. J. Psychophysiol. 14, 227.
Marino, A.A., Becker, R., 1977. Biological effects of extremely low frequency electric and magnetic fields: a review. Physiol. Chem. Phys. 9 (2), 131–147.
Marino, A.A., Nilsen, E., Chesson Jr., A.L., et al., 2004. Effect of low-frequency magnetic fields on brain electrical activity in human subjects. Clin. Neurophysiol. 115, 1195–1201.
Martin, G.V., Houle, T., Nicholson, R., Peterlin, A., Martin, V.T., 2013. Lightning and its association with the frequency of headache in migraineurs: an observational cohort study. Cephalalgia 33 (6), 375–383.
McLeod, K.J., Lee, R.C., Ehrlich, H.P., 1987. Frequency dependence of electric field modulation of fibroblast protein synthesis. Science 236, 1465–1469.
Miller, C., 2000. An overview of the potassium channel family. Genome Biol. 1 (4).
Nagano, I., Yagitani, S., Ozaki, M., Nakamura, Y., Miyamura, K., 2007. Estimation of lightning location from single station observations of sferics. Electron. Commun. Japan (Part I: Communications) 90 (1), 25–34.
Nasser, E., 1970. Fundamentals of Gaseous Ionization and Plasma Electronics. Wiley, New York.
Navarro, A. Enrique, Segura, J., Portolés, M., de Mateo, Claudio Gómez-Perretta, 2003. The microwave syndrome: a preliminary study in Spain. Electromagn. Biol. Med. 22 (2–3), 161–169.
Noda, M., Ikeda, T., Kayano, T., Suzuki, H., Takeshima, H., Kurasaki, M., Takahashi, H., Numa, S., 1986. Existence of distinct sodium channel messenger RNAs in rat brain. Nature 320, 188–192.
Orville, R.E., Spencer, D.W., 1979. Global lightning ash frequency. Mon. Weather Rev. 107, 934–943.
Pall, M.L., 2013. Electromagnetic fields act via activation of voltage-gated calcium channels to produce beneficial or adverse effects. J. Cell. Mol. Med. 17, 958–965.
Panagopoulos, D.J., Messini, N., Karabarbounis, A., Filippetis, A.L., Margaritis, L.H., 2000. A mechanism for action of oscillating electric fields on cells. Biochem. Biophys. Res. Commun. 272 (3), 634–640.
Panagopoulos, D.J., Karabarbounis, A., Margaritis, L.H., 2002. Mechanism for action of electromagnetic fields on cells. Biochem. Biophys. Res. Commun. 298 (1), 95–102.
Panagopoulos, D.J., Chavdoula, E.D., Margaritis, L.H., 2010. Bioeffects of mobile telephony radiation in relation to its intensity or distance from the antenna. Int. J. Radiat. Biol. 86 (5), 345–357.
Panagopoulos, D.J., Johansson, O., Carlo, G.L., 2013a. Evaluation of specific absorption rate as a dosimetric quantity for electromagnetic fields bioeffects. PLoS One 8 (6), e62663. http://dx.doi.org/10.1371/journal.pone.0062663.
Panagopoulos, D.J., Karabarbounis, A., Lioliousis, C., 2013b. ELF alternating magnetic field decreases reproduction by DNA damage induction. Cell Biochem. Biophys. 67, 703–716.
Panagopoulos, D.J., 2013. Electromagnetic interaction between environmental fields and living systems determines health and well-being. Electromagnetic Fields: Principles,

Engineering Applications and Biophysical Effects. Nova Science Publishers, New York, USA.
Panagopoulos, D.J., Johansson, O., Carlo, G.L., 2015a. Polarization: a key difference between man-made and natural electromagnetic fields, in regard to biological activity. Sci. Rep. 5:14914. http://dx.doi.org/10.1038/srep14914.
Panagopoulos, D.J., Johansson, O., Carlo, G.L., 2015b. Real versus simulated mobile phone exposures in experimental studies. Biomed. Res. Int. 2015, 607053.
Pathak, P.P., Rai, J., Varshneya, N.C., 1982. VLF radiation from lightning. Geophys. J. R. Astron. Soc. 69, 197–207.
Penafiel, L.M., Litovitz, T., Krause, D., Desta, A., Mullins, M.J., 1997. Role of modulation on the effect of microwaves on ornithine decarboxylase activity in L929 cells. Bioelectromagnetics 18 (2), 132–141.
Pelz, J., Swantes, H.J., 1986. Statistische Untersuchungen iiber das Auftreten von Stumpfund Phantomschmerzen, sowie ihre mogliche Abhangigkeit von luftelektrischen Erscheinungen (Statistical investigations on the occurrence of stump pain and phantom limb pain and their possible dependence on air-electrical phenomena). Kleinheubacher Berichte 29, 367–375.
Persinger, M.A., 2012. Brain electromagnetic activity and lightning: potentially congruent scale - invariant quantitative properties. Front. Integr. Neurosci. 6 (19), 1–7.
Polk, C., 1991. Biological effects of low level frequency electric and magnetic fields. IEEE Trans. Educ. 34 (3), 243–249.
Presman, A.S., 1977. Electromagnetic Fields and Life. Plenum Press, New York.
Regel, S.J., Tinguely, G., Schuderer, J., Adam, M., Kuster, N., Landolt, H.P., et al., 2007. Pulsed radio-frequency electromagnetic fields: dose-dependent effects on sleep, the sleep EEG and cognitive performance. J. Sleep Res. 16, 253–258.
Reiser, H., Dimpfel, W., Schober, F., 1995. The influence of electromagnetic fields on human brain activity. Eur. J. Med. Res. 1, 27–32.
Reiter, R., 1960. Meteorobiologie und Elektrizität der Atmosphäre. (Meteorobiology and atmospheric electricity). Akademische Verlagsgesellschaft Geest & Portig, Leipzig.
Reiter, R., 1995. Biological effects of electromagnetic man-made noise, atmospherics, and small ions. In: Volland, H. (Ed.), Handbook of Atmospheric Electrodynamics. CRC Press, Boca Raton.
Roggeveen, S., van Os, J., Viechtbauer, W., Lousberg, R., 2015. EEG changes due to experimentally induced 3G mobile phone radiation. PLoS One 10 (6), e0129496. http://dx.doi.org/10.1371/journal.pone.0129496.
Ruhenstroth-Bauer, G., Baumer, H., Kugler, J., Spatz, R., Sönning, W., Filipiak, B., 1984. Epilepsy and weather: a significant correlation between the onset of epileptic seizures and specific atmospherics. Int. J. Biometeorol. 28, 333.
Ruhenstroth-Bauer, G., Baumer, H., Burkel, E.M., Sönning, W., Filipiak, B., 1985. Myocardial infarction and the weather: a significant positive correlation between the onset of heart infarction and 28 kHz atmospherics. Clin. Cardiol. 8, 149.
Ruhenstroth-Bauer, G., Mees, K., Sandhagen, R., Filipiak, B., 1987. Demonstration of statistically significant correlations between 8 and 12 kHz atmospherics and sudden deafness. Z. Naturforsch. 42, 999–1000.
Salama, O.E., Abou El Naga, R.M., 2004. Cellular phones: are they detrimental? J. Egypt. Public Health Assoc. 79 (3–4), 197–223.
Schienle, A., Stark, R., Walter, B., Vaitl, D., 1997. Effects of low-frequency magnetic fields on electrocortical activity in humans: a sferics simulation study. Int. J. Neurosci. 90, 21.
Schienle, A., Stark, R., Vaitl, D., 1998. Biological effects of very low frequency (VLF) atmospherics in humans: a review. J. Sci. Explor. 12 (3), 455–468.
Schienle, A., Stark, R., Vaitl, D., 2001. Sferics provoke changes in EEG power. Int. J. Neurosci. 107 (1–2), 87–102.
Schumann, W.O., 1952. Uber die strahlunglosen eigenschwingungen einer leitenden Kugel, die von einer Luftschicht und einer Ionospharenh ulle umgeben ist. Z. Naturforsch. 7A, 6627–6628.
Singh, K., Nagaraj, A., Yousuf, A., Ganta, S., Pareek, S., Vishnani, P., 2016. Effect of electromagnetic radiations from mobile phone base stations on general health and salivary function. J. Int. Soc. Prev. Community Dent. 6 (1), 54–59.
Stanford, J.L., 1971. Polarization of 500 kHz electromagnetic noise from thunderstorms: a new interpretation of existing data. J. Atmos. Sci. 28, 116–119.
Stavroulakis, P., 2003. Biological Effects of Electromagnetic Fields. Springer, New York.
Stryer, L., 1996. Biochemistry. fourth ed. W.H. Freeman and Co, N.Y., U.S.A.
Tomko, A.A., Hepner, T., 2001. Worldwide monitoring of VLF-LF propagation and atmospheric noise. Radio Sci. 36 (2), 363–369.
Vaitl, D., Propson, N., Stark, R., Schienle, A., 2001a. Natural very-low-frequency sferics and headache. Int. J. Biometeorol. 45, 115–123.
Vaitl, D., Propson, N., Stark, R., Walter, B., Schienle, A., 2001b. Headache and sferics. Headache 41, 845–853.
Valentini, E., Curcio, G., Moroni, F., Ferrara, M., De Gennaro, L., Bertini, M., et al., 2007. Neurophysiological effects of mobile phone electromagnetic fields on humans: a comprehensive review. Bioelectromagnetics 28, 415–432.
Veyret, B., Bouthet, C., Deschaux, P., de Seze, R., Geffard, M., Joussot-Dubien, J., le Diraison, M., Moreau, J.M., Caristan, A., 1991. Antibody responses of mice exposed to low-power microwaves under combined, pulse-and-amplitude modulation. Bioelectromagnetics 12 (1), 47–56.
Viel, J.F., Clerc, S., Barrera, C., Rymzhanova, R., Moissonnier, M., Hours, M., Cardis, E., 2009. Residential exposure to radiofrequency fields from mobile phone base stations, and broadcast transmitters: a population-based survey with personal meter. Occup. Environ. Med. 66, 550–556.
Von Mackensen, S., Hoeppe, P., Maarouf, A., Tourigny, P., Nowak, D., 2005. Prevalence of weather sensitivity in Germany and Canada. Int. J. Biometeorol. 49, 156–166.
Walach, H., Betz, H.D., Schweickhardt, A., 2001. Sferics and Headache, a prospective study. Cephalalgia 21, 685–690.
Watt, A.D., 1960. ELF electric fields from thunderstorms. J. Res. Nat. Bur. Stand. 64D (5), 425–433.
Wever, R., 1979. The Circadian System of Man: Results of Experiments Under Temporal Isolation. Springer-Verlag.
Williams, E.R., 1992. The Schumann resonance: a global tropical thermometer. Science 256, 1184–1187.
Wood, T.G., Inan, U.S., 2004. Localization of individual lightning discharges via directional and temporal triangulation of sferic measurements at two distant sites. J. Geophys. Res. Atmos. 109 (D21).
Yang, A.C., Fuh, J.L., Huang, N.E., Shia, B.C., Peng, C.K., Wang, S.J., 2011. Temporal associations between weather and headache: analysis by empirical mode decomposition. PLoS One 6 (1), e14612.