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Natural ELF Fields in the Atmosphere and in Living Organisms

Colin Price\(^1\), Earle Williams\(^2\), Gal Elhalel\(^1\) and Dave Sentman\(^3\)*

\(^1\)Department of Geophysics, Porter School of the Environment and Earth Sciences, Tel Aviv University, Israel
\(^2\)Parsons Lab, MIT, Cambridge, USA
\(^3\)Department of Geophysics, University of Alaska, Fairbanks, USA

*Deceased

Corresponding Author: C. Price, cprice@flash.tau.ac.il

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Abstract: Most electrical activity in vertebrates and invertebrates occurs at extremely low frequencies (ELF), with characteristic maxima below 50Hz. The origin of these frequency maxima is unknown and remains a mystery. We propose that over billions of years during the evolutionary history of living organisms on Earth, the natural electromagnetic resonant frequencies in the atmosphere, continuously generated by global lightning activity, provided the background electric fields for the development of cellular electrical activity. In some animals the electrical spectrum is difficult to differentiate from the natural background atmospheric electric field produced by lightning. In this paper we present evidence for the link between the natural ELF fields and those found in many living organisms, including humans.

KEYWORDS: Schumann Resonances, lightning, ELF, biological organisms
Introduction

One of the fundamental questions in biological sciences, and more specifically in brain research, is why organisms exhibit characteristic extremely low frequency (ELF) oscillations in electric activity (Nunez, 1981; Bullock, 2002). Although a tremendous amount of research has been invested into understanding the role of the different brain waves on the function of biological systems, very few have asked the fundamental question regarding the origin of these electromagnetic oscillations in living organisms.

It is surprising that many different types of species (vertebrates and invertebrates) exhibit similar low frequency electrical wave activity, irrespective of their brain size, brain complexity, or even the existence of a cortex. What can it mean that most vertebrates, from fish and frogs to homo-sapiens show essentially very similar electrical activity (Bullock, 2002). Zooplankton in the oceans exhibit electrical activity peaking around 7 and 14 Hz (Fig1a) (Freund et al., 2002). Larger vertebrates and invertebrates (sea lion, snake, shark, and octopus) (Fig. 1b) (Bullock, 2002) also show spectra that occur primarily below 50Hz, while in human beings (Fig. 1c), all spectra show similar patterns with peaks below 50Hz. What is interesting to note is the dominant peak close to 8Hz in all examples. There are obvious differences between the electrical activity of the different species, however there are also many similarities. In particular, the electrical activity is not equal at all frequencies below 50Hz, and the living organisms appear to prefer certain frequency bands over others. Amplitude of the spectra is the only obvious difference among vertebrate classes, with the highest amplitudes occurring in mammals. Vertebrates almost invariably have a maximum between 5-15Hz that falls off at higher frequencies by more than a factor of two for each octave to about 1/10 at 100Hz (Bullock, 2002). Most electrical activity in humans occurs in a frequency range below 50 Hz, with alpha waves (8-13Hz) representing deep relaxation, meditation and stress relief (Banquet, 1973), beta waves (14-25Hz) representing normal alert mental state (Gola et al., 2012), gamma waves (30-100 Hz) associated with perception and consciousness (Dehaene, 1993), delta waves (0.5-4 Hz) representing deep sleep (Blake et al. 1939), and theta waves (4-8Hz) representing creativity and dreaming states (Molle et al., 2002). The brain wave
activity is obviously limited to certain regimes depending on the activity of the subject, and therefore only some rhythms are observed at any one time.

We also know that the nature of the spectrum can change dramatically depending on the physical and mental activity of the subject. It is clear from human research that the alpha waves are dominant when in a state of deep relaxation (Banquet, 1973). Research on humans and has shown that as the amount of halothane (anesthetic) increases the brain's activity shows a shift from the normal 10 Hz alpha signals to a predominant 7-8 Hz signal (Fig. 2) (Nunez et al., 1978; Nunez, 1981).

Primitive forms of life on planet Earth could be hypothesized to have been in a state close to "deep sleep" implying a spectrum closer to those in Figure 2 than the normal alpha spectrum that is closer to 10Hz (Griffiths et al., 1991). The importance of this shift will become apparent later in this paper. It should also be noted that often the brain shows increased activity around 26Hz (Figure 1c), close to the frequency of the fourth mode of the Schumann resonances.

**Schumann Resonance**

In 1952 W.O. Schumann theoretically calculated that given the highly conductive Earth and ionosphere above, the Earth-ionosphere cavity should “ring” at specific resonant frequencies. Schumann (1952) calculated that these harmonic standing waves should be in the extremely low frequency (ELF) range, and by assuming a lossless cavity (no absorption by the ionosphere) he predicted the first mode of resonant frequencies to occur at 10 Hz. The first spectral measurements by Balser and Wagner (1960) actually showed that the resonant frequencies occur at approximately 8, 14, 20, 26, ..., Hz, due to the partial absorption of the ionosphere. The source of these Schumann resonance (SR) waves is global lightning activity, and the electromagnetic waves emitted from lightning channels with some vertical component of charge transfer. At these frequencies there is very little attenuation in the atmosphere (0.1 dB/Mm or 1 dB over 10,000 km), hence the ELF waves from lightning anywhere on the planet manage to propagate to any other location guided in the natural waveguide formed by the ionosphere and the Earth's surface. The constructive interference of these radio waves as they travel around the Earth
(circumference 40,000 km) results in the standing waves and their harmonics ($\lambda \approx \frac{2\pi}{nc/40,000}$) known as the Schumann resonances. With 50-100 lightning flashes every second somewhere on the globe (Christian et al., 2003), the SR background field exists at all times in the atmosphere (Fraser-Smith and Bannister, 1998) (Figure 3).

**Figure 1.** a. Power spectra related to the electrical activity in a) zooplankton (adopted from Nunez et al., 1978), b) vertebrates (seal lion, snake, shark) and invertebrates (octopus) (adopted from Bullock, 2002), and c) human beings measured at 3 different locations on the head showing one-minute averages (y-axes).
Figure 2. Brain activity (power spectra) during 45 minutes (y-axes) for different amounts of halothane (anesthetic) induced in a human subject. The concentration of halothane varies as a sine wave with a period of 16 minutes (adopted from Nunez et al., 1978).

Figure 3. Average amplitude spectrum of the lower-ELF radio noise at Søndrestrømfjord, Greenland, during January, 1990 (Fraser-Smith and Bannister, 1998). The Schumann resonances are clearly seen below 50Hz, while the spikes at specific frequencies are man-made sources, including the Russian 82Hz ELF transmitter on the Kola Peninsula.
The SR spectrum varies in amplitude and frequency depending on the time of day, season, and relative location on the Earth compared with the thunderstorm regions (Price and Melnikov, 2004). We know today that global lightning activity is concentrated over the tropical landmasses (Southeast Asia, Africa and South America) (Christian et al., 2003) with only 10% of global lightning occurring over the Earth's oceans. At distances larger than a few thousand kilometers from the thunderstorms the electromagnetic field is primarily composed of a horizontal magnetic field and a vertical electric field. Due to the modal structure of the SR standing waves and the orthogonality of the electric and magnetic fields, the SR at a distance of 10,000km from the tropics will show a maximum at 8Hz for the magnetic field, however, a minimum at 8Hz for the electric field (Sentman, 1985). The opposite will be true at a distance of 20,000 km from the lightning discharge. The ratio of the amplitudes of the various SR modes changes as the source-observer distance changes. Hence the SR spectra are not the same at all locations, even if the global lightning activity remains constant during the period of observation. Furthermore, changes in the peak frequencies can occur either due to changes in the source-receiver separation, to changes in the size of the thunderstorm regions (Satori, 1996), or to changes in the properties of the ionosphere (the waveguide) (Roldugin et al., 2004). However, these changes in peak frequencies of the various modes are less than 1 Hz and therefore can be assumed to be quasi-stationary in time and location.

The SR has existed on the Earth ever since the formation of our atmosphere and our ionosphere. Both these characteristics have been stable since the time of formation of life the Earth (Kasting and Siefert, 2002). The atmosphere was initially produced by out-gassing from volcanoes (Kasting, 1993). Even today volcanoes are observed to be accompanied by lightning discharges (McNutt and Williams, 2010). However, the natural atmospheric convection in the early Earth would also have resulted in the electrification of clouds and the production of lightning discharges. The ionosphere, and hence the waveguide necessary for producing the SR, is maintained by energetic solar radiation colliding with atoms and molecules in our upper atmosphere, producing ions and free electrons that result in the reflection of electromagnetic waves in the ELF range (Cummer, 2000). Hence it is likely that the Schumann resonances have existed since the beginning of life on our planet, or at least 2-3 billion years if not longer.
What is fascinating is the similarity between the observed SR frequencies and the electrical activity in the organisms presented above. Is this similarity pure coincidence? Early researcher in the field already recognized this similarity, and even performed research on people to understand the connection with human activity (Reiter, 1953; Konig, 1974; Wever, 1970; Konig et al., 1981; Cherry, 2000, 2003). Additional experiments were carried out with birds (Wever, 1973) and flies (Engelman et al., 1996). We will discuss some of these experiments below.

**Stochastic Synchronization**

Deep convection, lightning activity, and hence the SR, have likely existed for billions of years on Earth (Urey, 1952), providing a natural background ELF field around the globe. This natural field by definition exhibits specific frequency maxima (see Figure 3) with the fundamental mode being around 8Hz. Could biological systems have used this natural field to train their own systems how to operate?

Among numerous nonlinear effects in nature, synchronization is the phenomenon that is probably the most often observed in many different systems (Strogatz, 1997). Synchronization represents the inter-connection between two objects that are oscillating in time. Synchronization occurs when there exists a fixed phase relation between the two objects. In the 17th century, Huygens was the first to study synchrony when he noticed the phase locking of two pendulum clocks hung on the same wall. There had to be some coupling between the oscillators in order for them to become phase-locked and hence synchronized. In the case of the clocks, the weak coupling was the transmission of weak vibrations through the wall from one clock to the other. These vibrations were produced by the mechanical "ticks" produced by the clocks.

While synchronization has been used in natural and man-made systems [Blekhman, 1988; Glass and Mackey, 1988], in biological systems synchronization can start from the microscopic level of cell populations [Soen et al, 1999], single neurons [Elson et al, 1998; Neiman et al, 1999], to large neural networks [Tass et al, 1998], human cardio-respiratory dynamics [Schafer et al, 1998], and even the behavior of large populations of living organisms [Winfree, 1980].
Hence, synchronization represents a mechanism of self-organization in complex systems [Haken, 1983], significantly decreasing the degrees of freedom of a system due to interactions with the environment, or interactions between subsystems. The classical theory of synchronization operates with so-called self-sustained periodic oscillators (Rosenblum et al., 1996). If a self-sustained oscillator is influenced by an external periodic force of appropriate amplitude and frequency, the oscillations of the system will synchronize in phase with the external signal. We can therefore define synchronization as frequency entrainment and phase locking.

We propose that over evolutionary time scales biological systems may have become phase locked to the background atmospheric electric fields defined by the Schumann resonances. The SR has been the only persistent electromagnetic field available for such synchronization over evolutionary time scales. Furthermore, given that early lifeforms evolved first in the oceans, it should be noted that ELF waves of planetary wavelength can penetrate hundreds of meters into the photic zone of the oceans. The skin depth of penetration for electromagnetic waves is defined by $d = \frac{503 \sqrt{1/f \sigma}}{\sqrt{m}}$ where $\sigma$ is the conductivity (S/m), and f is the frequency in Hz. For seawater ($\sigma = 3.3$ S/m) and blood ($\sigma = 0.7$ S/m) the skin depth of an 8Hz electromagnetic wave is approximately 100 m and 210 m, respectively. This implies that organisms in the photic zone in seawater (up to 100 m depth) will feel the SR waves, and that the insides of organisms will be exposed to similar field amplitudes as those found in the atmosphere. Hence, lifeforms in the oceans are also continuously exposed to these SR fields.

**Stochastic resonance**

Although the idea of stochastic synchronization sounds appealing, the Schumann resonance fields in the atmosphere are extremely small. The amplitude of the magnetic fields are measured in picotesla (1 pT = 10^{-12} Tesla), 10 million times weaker than the earth’s quasi-static geomagnetic field, while the electric fields are of the order of mV/meter. Even with stochastic synchronization, how could such small atmospheric fields influence biological systems?

Stochastic resonance occurs when a nonlinear system is subjected to a weak periodic signal that is normally not detectable, but it becomes detectable due to a resonance
phenomenon between the stochastic noise and the weak deterministic periodic signal (Benzi et al., 1981). Early studies of stochastic resonance showed that increasing background noise levels often resulted in increases in the output signal strength we are looking for (Bulsara and Gammaitoni 1996).

Noise may be random or systematic. Generally we think of noise as interfering with the transmission and detection of signals. However, stochastic resonance implies the opposite. In fact, the addition of the appropriate amount of noise can amplify a signal and hence help in its detection in a noisy environment (Gammaitoni et al., 2009). And due to its robustness and simplicity, stochastic resonance is used by mother-nature on almost all scales.

By tuning the amplitude of the external noise to the internal properties of the system, the periodic driving mechanism and the external noise can interact with each other, transferring energy from the noise spectrum into a single frequency which is coherent with the signal. This interaction between external noise and the signal can result in a clear maximum in the power spectrum of the output signal, increasing the signal to noise ratio. However, the amplitude of the noise is also important, and if the noise is too large, the signal will be destroyed.

In our hypothesis we propose that lightning induced ELF fields and the Schumann resonances may act as the "noise" used by biological systems via the stochastic resonance phenomenon. This constant source of noise over evolutionary time scales may have influenced the evolution of many biological systems and determined to a large part the electrical activity observed today.

Evidence for a connection between natural ELF fields and those in living organisms

As mentioned above, already in the 1950s and 1960s experiments were being carried out in light of the similarities between the natural ELF fields discovered in the atmosphere, and the electrical activity in humans. Some of the most interesting and robust experiments were performed on the Circadian Rhythms (Weber, 1974). Weber built two identical rooms underground with no window and no sign of day or night.
In both rooms was placed a volunteer for one month, with the only communication being letters under the door. The activity (sleep, awake) was monitored, as well as the body temperature. These parameters normally have a 24 hour cycle when we have the dark-light clock to synchronize our activity. However, with no signs of day or night, the biological clock starts to drift to longer days (25, 26, 27 hour days). This is shown in Fig. 4, where the x-axis is the hour of the day, and the y-axis is the day of the month. In the first week of the experiment the biological clock monitored in the subjects changed to 26.6 hour days. Then, in one of the rooms a 10 Hz electric field generator was turned on continuously during the second week. The biological clock appeared to stabilize and return back towards 24 hours (25.8 hours). After another week the field was turned off, and the biological clock drifted rapidly to 36.7 hour days. The biological clock of the volunteer in the other room remained constant throughout the three week experiment.

![Figure 4](image-url.com)

Figure 4. The circadian rhythms of a human, observed during constant light conditions without a 10 Hz field during the first and third periods, and under the influence of an artificial 10 Hz electric field during the second period. The horizontal bars represent the hours of activity and sleep each day, while the triangles represent the minimum and maximum body temperature. Adopted from Weber (1973).

This experiment was repeated with green finch birds (Weber, 1973) and later with flies (Engelmann et al., 1996), showing similar changes in the Circadian Rhythms due to the influence of a 10 Hz electric signal. It should be noted that in all these early experiments the field induced was at 10 Hz and not 8 Hz. The reason for this is that Schumann (1952) originally predicted that the first ELF resonance due to lightning should be at 10Hz, since he assumed the ionosphere to be a perfect reflector.
However, this is not the case in reality, and due to some absorption, the true first mode frequency is around 7.8Hz.

More recent studies showing a connection between biological organisms and the Schumann resonance frequencies have been published by Segal et al. (2016a, 2016b) related to both stroke and spinal cord injury (SCI) in rats. In the second study the motor recovery of rats with SCI was monitored over a 2 month period. Magnetic fields were applied to the injured rats at two different frequencies. The first was 15.72 Hz (twice the first mode of the SR) and 26 Hz (the fourth mode of the SR). The magnetic fields at these frequencies were applied for only 8 minutes per day, 5 days per week, in the first month, and then 20 min per day 5 days per week in the second month. Significant improvements of the motor skills of the rats were observed when the fields were applied, relative to the control experiments with no magnetic fields applied. Furthermore, while the recovery of the rats reached a limit after 60 days with the 15.72 Hz field, the recovery continued to improve when the 26Hz field was used (Figure 5). In the stroke experiments with rats (Segal et al., 2016a) the frequencies with the best impacts were 0.5 x 7.8Hz and 2 x 7.8 Hz.

Recently our group (Elhalel et al. 2019) has also shown significant impacts of the 7.8 Hz magnetic fields on rat cardiac myocytes. In our studies we imposed a 7.8 Hz magnetic field on 3-4 day old cultures, and performed three main experiments. The first was the observation of the spontaneous mechanical contractions of the cardiac cells using an optical microscope. Observations with and without the external field were performed. The second experiment was to observe the spontaneous Calcium ion (Ca+) transients using a fluorescence microscope, as a function of time, with and without the external field. And finally, the third experiment studied the damage caused to the cardiac cells following stress induced on the cells due to hypoxia or the addition of H2O2, both with and without the external 7.8Hz field. When the external magnetic field was applied effects were seen almost immediately.
Figure 5. Clinical tests showing the motor recovery from spinal cord injury in rats (adopted from Segal et al., 2016b). The Y-axis represents a measure of motor skill improvement. The scale (0-12) represents stage of recovery based on animal joint movement, hind limb movements, stepping, forelimb and hind limb coordination, trunk position and stability, paw placement and tail position.

Within 30-40 minutes of applying the magnetic field the spontaneous contractions ceased, while the Ca+ transients reduced by 80%. But perhaps the most interesting finding is that the external field reduced the stress induced damage by about 40% relative to the control. This damage is quantified by measuring the concentrations of Creatine Kinase (CK) in the medium around the cells. This same CK increases dramatically in human blood for people suffering heart attacks. This decrease in damage implies that the external SR fields may supply a protective "shield" to cells under stress. It should be noted that there was no impact of the field strength (between 20pT to 200 nT) on the results, while the induced frequency played a significant role.

Summary and Discussion

We propose a controversial, and perhaps revolutionary, idea to explain the origin of the frequency of electrical activity in many different living creatures on our planet. Many species (from zooplankton to humans) exhibit electrical activity in the ELF range below 50Hz, with significant maxima in their power spectra focused at specific frequencies. These frequencies show surprising similarity to the natural ELF spectra in the atmosphere produced by lightning (compare Fig. 1b (shark) and Fig. 3). The mechanisms that can explain such a relationship may include stochastic synchronization and stochastic resonance.
We hypothesize that the background ELF fields in the atmosphere had a major role in the evolution of biological systems. However, it is likely that the influence of the atmospheric ELF fields was greatest at the early stages of evolution, when species were relatively simple and primitive. The SR frequencies are set by the speed of light and size of the Earth, implying that organisms have been exposed to specific frequencies for billions of years. However, as a result of evolution some species may have shifted their preferred frequency of electrical activity, while others may have locked on to a specific mode of the atmospheric field. Furthermore, the atmospheric waveguide itself has likely changed over the last billion years, although as stated above the frequencies of the SR are primarily controlled by the Earth's radius that has remained constant over billions of years.

It should also be noted that there are other natural sources of ELF radiation in the atmosphere, particularly the ionospheric Alfen resonances (IARs) (Bosigner et al., 2002; Fedorov et al., 2006) and also likely produced by lightning in the atmosphere.

All studies described above present evidence that very weak alternating magnetic fields influence biological processes. Unfortunately, a physical mechanism explaining these findings is still absent. The main obstacle in uncovering the physical explanation is the extremely weak amplitude of the magnetic fields used in the experiments, with an energy much lower than the surrounding noise factors and characteristic energy scales, such as the thermal fluctuations of the charged particles and the resulting Johnson–Nyquist noise (known in the literature as the ‘kT problem’), the electrical noise (magnetic fields produced by the brain for example are of the same order of the SR field (~ pT) while fields produced by cardiomyocyte excitation is two orders of magnitude higher (~100pT)) and chemical energy required for biological processes (Adair, 1991; Binhi, et al., 2007; Scalia et al., 2012). A detailed description of electric and magnetic field strengths and noise levels can be found in Adair (1991). A few attempts have been made to address this problem and find a reasonable explanation for the phenomena. Del Giudice et al. (2002) suggested the ion-cyclotron resonance as a possible explanation, and water coherent domains which enable collision free movement and therefore overcoming the ‘kT problem’. Another possible explanation involves biogenic magnetite and other ferromagnetic particles (Binhi, et al., 2007).
Bifurcation behaviour was suggested as a possible candidate due to the non-linear dynamics of biological systems (Kaiser, 1996). More explanations include eddy currents, ion interference and radical pair reactions. For a detailed review see Binhi & Rubin (2007).

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