Asteroid impact, Schumann resonances and the end of dinosaurs

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Abstract

We estimate the expected magnitudes of the Schumann resonance fields immediately after the Chicxulub impact and show that they exceed their present-day values by about $5 \times 10^4$ times. Long-term distortion of the Schumann resonance parameters is also expected due to the environmental impact of the Chicxulub event. If Schumann resonances play a regulatory biological role, as some studies indicate, it is possible that the excitation and distortion of Schumann resonances as a result of the asteroid/comet impact was a possible stress factor, which, among other stress factors associated with the impact, contributed to the demise of dinosaurs.

Keywords: Schumann resonances, ELF electromagnetic fields, Chicxulub impact, Dinosaur extinction

1. Introduction

Dinosaurs have been the dominant group of living organisms on the Earth for over 160 million years (Myr). There were over 1000 species of dinosaurs distributed worldwide. The direct evolutionary descendants of non-avian dinosaurs, birds still make up one of the most proliferate and diverse group of vertebrates. However, non-avian dinosaurs themselves suddenly disappeared about 66 Myr ago [1].

There are astounding number and variety of hypotheses about causes of the dinosaur extinction [1, 2]. However, the current research is concentrated around three major ones: 1) an impact of a giant bolide (asteroid or comet) [3].

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4, 5]; 2) Volcanic activity in modern-day India’s Deccan Traps [6]; 3) Marine regression (drop in sea level) and the corresponding global environmental deterioration [7, 8].

All three of the above stress factors occurred at the end of the Cretaceous, which makes it difficult to disentangle their relative importance in the mass extinction event that occurred at the Cretaceous-Palogene (K-Pg) boundary (formerly Cretaceous-Tertiary or K-T boundary). It is noteworthy that there is little evidence that bolide impacts on the Earth correlate well with episodes of mass extinction other than K-Pg (there have been five mass extinctions in the past 550 Myr), while both sea regression and massive volcanism do correlate well with such episodes [2].

Nevertheless, modern research [1, 9] found support for a bolide impact as the primary factor of the end-Cretaceous mass extinction. Evidence of the bolide impact, coinciding in time with dinosaur extinction, is ubiquitous, including the huge 150 km wide Chicxulub crater in the Yucatán Peninsula in Mexico, impact related iridium anomaly worldwide, sediments in various areas of the world dominated by impact melt spherules and an unusually large amount of shocked quartz.

Yet another evidence of the enormous power of the Chicxulub impact has been discovered recently [10]. After the impact, billions of tons of molten and vaporized rock was thrown in all directions. After about ten minutes, these debris reached Tanis, a place at a distance of about 3 000 km from the impact. Bead-sized material, glassy tektites, fell from the sky, piercing everything in its path. Fossil fish at Tanis, densely packed in the deposit, are found with the impact-induced spherules embedded in their gills.

At about the same time, strong seismic waves, generated by the Chicxulub impact, arrived at Tanis generating seiche inundation surge with about 10 m amplitude [10].

Observations at Tanis expand our knowledge of the destructive effects of the Chicxulub impact, identifying the potential mechanism for sudden and extensive damage to the environment, delivered minutes after the impact to widely separated regions.

Our goal in this short note is to show that the global extinction event could have had another very rapidly delivered global precursor, namely the excitation of Schumann resonances with currently unknown but potentially dangerous biological effects.
2. Schumann resonances

It is useful to introduce the following complex combination of the electric and magnetic fields, called Riemann-Silberstein vector in [11]:

\[
\vec{F} = \sqrt{\frac{2}{\epsilon}} \left( \frac{\vec{D}}{\sqrt{2\epsilon}} + \frac{\vec{B}}{\sqrt{2\mu}} \right) = \vec{E} + ic\vec{B},
\]

(1)

where \( \epsilon \) is the dielectric constant, \( \mu \) is the magnetic permeability, and \( c = 1/\sqrt{\epsilon \mu} \) is the light velocity in a homogeneous and static medium in which \( \vec{D} = \epsilon \vec{E} \) and \( \vec{B} = \mu \vec{H} \).

In terms of the Riemann-Silberstein vector, the Maxwell equations read

\[
i\frac{\partial \vec{F}}{\partial t} = c\nabla \times \vec{F}, \quad \nabla \cdot \vec{F} = 0.
\]

(2)

It is well known that the process of solving the Maxwell equations can be facilitated by the use of potentials. The Riemann-Silberstein vector can be expressed in terms of the Hertz vector (superpotential) as follows [11]:

\[
\vec{F} = \left[ \frac{i}{c} \frac{\partial}{\partial t} + \nabla \times \right] \left( \nabla \times \vec{\Pi} \right).
\]

(3)

It follows from the first Maxwell equation in (2) that the Hertz superpotential \( \vec{\Pi} \) must satisfy the equation

\[
\left( \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \Delta \right) \left( \nabla \times \vec{\Pi} \right) = 0.
\]

(4)

The name ”superpotential” indicates that electric and magnetic fields are expressed through the second derivatives of the superpotential, and not through the first derivatives, as in the case of standard potentials.

Much like more familiar four-potential, Hertz vector is not determined uniquely by (3). In fact the group of gauge transformations of the Hertz

\[\text{[11]}\]

\[\text{[12]}\]

\[\text{[13]}\]
vector that leave the Riemann-Silberstein vector unchanged is very large \[11, 14\]. In particular, when dealing with radiation fields produced by localized sources, a very convenient choice is the assumption that the Hertz superpotential is radial \[11\]:

\[
\vec{\Pi}(\vec{r}, t) = \vec{r} \Phi(\vec{r}, t).
\] (5)

Then it follows from (4), since the operator \(\hat{\vec{L}} = \vec{r} \times \nabla\) commutes with the Laplacian, that the complex function \(\Phi(\vec{r}, t) = U(\vec{r}, t) + iV(\vec{r}, t)\) can be adjusted in such a way using the gauge freedom that it satisfies the wave equation \[15, 16\]:

\[
\left(\frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \Delta\right) \Phi = 0.
\] (6)

Using well-known expressions of differential operators in spherical coordinates, we get from (3) and (5)

\[
F_r = -\frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial (r \Phi)}{\partial \theta} \right) - \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 (r \Phi)}{\partial \phi^2},
\] (7)

which by using (6), and assuming harmonic dependance of fields on time of the form \(e^{\pm \omega t}\), can be transformed into

\[
F_r = \left[ \frac{\partial^2}{\partial r^2} + \omega^2 \frac{1}{c^2} \right] (r \Phi).
\] (8)

The real and imaginary parts of \(\Phi, U\) and \(V\) respectively, are called electric and magnetic Debye (super)potentials. They are scalars under the (proper) three-dimensional rotations, but have complicated transformation properties under the Lorentz boosts \[15\].

Schumann resonances are quasi-standing transverse magnetic modes in the Earth-ionosphere cavity, in which the radial component of the magnetic field equals to zero and thus (8) implies \(V = 0\). Then from (3)

\[
\vec{E} = \nabla \times (\nabla \times \vec{r}) U, \quad \vec{B} = \frac{1}{c^2} \frac{\partial}{\partial t} \nabla \times \vec{r} U,
\] (9)

and for the harmonic (complex) fields with \(e^{\pm i\omega t}\) time dependance we get

\[
E_r = \left[ \frac{\partial^2}{\partial r^2} + \frac{\omega^2}{c^2} \right] (rU), \quad E_\theta = \frac{1}{r} \frac{\partial}{\partial r} (rU), \quad E_\phi = \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} (rU),
\]

\[
B_\theta = \frac{i \omega}{c^2 \sin \theta} \frac{\partial U}{\partial \phi}, \quad B_\phi = -\frac{i \omega}{c^2} \frac{\partial U}{\partial \theta}.
\] (10)
The wave equation (6) for $U$ (with $e^{i\omega t}$ harmonic time dependance) can be solved by separation of variables in spherical coordinates. Namely, taking $U(\vec{r}, t) = \rho(r) Y_{lm}(\theta, \varphi) e^{i\omega t}$, where $Y_{lm}(\theta, \varphi)$ are spherical functions, and using

$$\Delta = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \Delta_\perp,$$

(11)

where $\Delta_\perp$ is the angular part of the Laplacian with $\Delta_\perp Y_{lm} = -l(l+1)Y_{lm}$, we get the spherical Bessel differential equation for the radial function $\rho(r)$:

$$\left[ \frac{d^2}{dr^2} + \frac{2}{r} \frac{d}{dr} + k^2 - \frac{l(l+1)}{r^2} \right] \rho(r) = 0, \quad k = \frac{\omega}{c}. \quad (12)$$

Therefore, inside the Earth-ionosphere cavity the Fourier component of $U$ has the form

$$U(\vec{r}, \omega) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \left[ A_{lm} h_l^{(1)}(kr) + B_{lm} h_l^{(2)}(kr) \right] Y_{lm}(\theta, \varphi), \quad (13)$$

where $h_l^{(1)}(kr)$ and $h_l^{(2)}(kr)$ are spherical Hankel functions of the first and second kinds, respectively. Since we have chosen $e^{i\omega t}$ for our time evolution, $h_l^{(1)}(kr)$ corresponds to the spherical incoming wave, while $h_l^{(2)}(kr)$ — to the spherical outgoing wave.

A real Earth-ionosphere waveguide have a very complicated configuration. Here we assume a simplified model [17]. Earth is considered as a perfectly conducting sphere of radius $R$. It is further assumed that the ionosphere begins with an inner radius of $R + h$ and is an infinite, uniform and isotropic plasma with complex dielectric constant (the imaginary part of which is proportional to the plasma conductivity [18]).

In the ionosphere we can have only outgoing spherical waves (Sommerfeld radiation condition [19]). Thus

$$U(\vec{r}, \omega) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} C_{lm} h_l^{(2)}(kr) Y_{lm}(\theta, \varphi) e^{i\omega t}, \quad r > R + h. \quad (14)$$

Schumann resonance frequencies are determined by boundary conditions at $r = R$ and $r = R+h$ [17] (for somewhat different approach, see [20]). namely, at $r = R$ the tangential components of the electric field must vanish. This leads to the condition

$$\left. \frac{\partial}{\partial r}(rU) \right|_{r=R} = 0. \quad (15)$$
At \( r = R + h \), the tangential components of the electric field \( \vec{E} \), and the tangential components of the magnetic field \( \vec{H} = \vec{B}/\mu \) must be continuous. If in the cavity \( \epsilon \approx \epsilon_0, \mu \approx \mu_0 \), while in the ionosphere \( \epsilon = \hat{\epsilon} \epsilon_0, \mu \approx \mu_0 \), in light of (10), the continuity conditions take the form

\[
\frac{\partial}{\partial r} (rU) \bigg|_{r=(R+h)_-} = \frac{\partial}{\partial r} (rU) \bigg|_{r=(R+h)_+},
\]

\[U(r = (R + h)_-) = \hat{\epsilon} U(r = (R + h)_+). \tag{16}\]

If we substitute (13) and (14) into (15) and (16), we get a homogeneous system of linear equations

\[
\begin{align*}
 u'_l(kR) A_{lm} + v'_l(kR) B_{lm} &= 0, \\
 u'_l(k(R + h)) A_{lm} + v'_l(k(R + h)) B_{lm} - v'_l(\sqrt{\hat{\epsilon}} k(R + h)) C_{lm} &= 0, \\
 u'_l(k(R + h)) A_{lm} + v_l(k(R + h)) B_{lm} - \sqrt{\hat{\epsilon}} v_l(\sqrt{\hat{\epsilon}} k(R + h)) C_{lm} &= 0. \tag{17}
\end{align*}
\]

Here we introduced the notations \[17\]

\[
u_l(x) = x h^{(1)}_l(x), \quad v_l(x) = x h^{(2)}_l(x), \quad u'_l(x) = \frac{du_l(x)}{dx}, \quad v'_l(x) = \frac{dv_l(x)}{dx}. \tag{18}\]

The system (17) has a non-trivial solution for \( A_{lm}, B_{lm}, C_{lm} \), only when the \( 3 \times 3 \) determinant of its coefficients equals zero. This requirement yields the following equation \[17\]

\[
u'_l(kR) v'_l(k(R + h)) - u'_l(k(R + h)) v'_l(kR) =
\]

\[
\frac{1}{\sqrt{\hat{\epsilon}} v_l(\sqrt{\hat{\epsilon}} k(R + h))} \left[ u'_l(k(R + h)) v_l(k(R + h)) - u_l(k(R + h)) v'_l(kR) \right]. \tag{19}\]

The solutions of this transcendental equation with respect to \( k \) determine eigenmodes \( \omega = c_0 k \) of the Earth-ionosphere resonator, which are called Schumann resonances. Here \( c_0 \) is the speed of light inside the resonator, which is the same as the light velocity in vacuum, \( c_0 = 1/\sqrt{\epsilon_0 \mu_0} \), for the approximations used. In general, \( \omega \) is a complex number. Its real part gives the eigenfrequency of the resonator, while the imaginary part determines the resonance width, since it corresponds to the damping factor of the eigenmode. The resonance width is characterized by the quality factor \( Q = \omega/\Delta \omega \), where \( \Delta \omega \) is the resonanse width at half maximum.
In the crude approximation of the infinite conductivity of the ionosphere, the right-hand-side of (19) vanishes and the equation for the eigenfrequencies simplifies. Further simplification can be achieved by using $h \ll R$, so that we can expand $u'(k(R + h)) \approx u'(kR) + u''(kR)kh$, and $v'(k(R + h)) \approx v'(kR) + v''(kR)kh$. Besides, it follows from the definitions of $u_l(x)$ and $v_l(x)$, that

$$u'_l(x) = h^{(1)}_l(x) + x \frac{dh^{(1)}_l(x)}{dx}, \quad u''_l(x) = 2 \frac{h^{(1)}_l(x)}{dx} + x \frac{d^2h^{(1)}_l(x)}{dx^2},$$

$$v'_l(x) = h^{(2)}_l(x) + x \frac{dh^{(2)}_l(x)}{dx}, \quad v''_l(x) = 2 \frac{h^{(2)}_l(x)}{dx} + x \frac{d^2h^{(2)}_l(x)}{dx^2}. \quad (20)$$

The second derivatives of the Hankel functions can be eliminated by using the fact that $\rho(r) = h^{(1)}_l(kr)$ and $\rho(r) = h^{(2)}_l(kr)$ satisfy the differential equation (12). This gives

$$u''_l(x) = \left( \frac{l(l + 1)}{x^2} - 1 \right) x h^{(1)}_l(x), \quad v''_l(x) = \left( \frac{l(l + 1)}{x^2} - 1 \right) x h^{(2)}_l(x). \quad (21)$$

Taking all this into account, in the case of perfectly conducting ionosphere, equation (19) simplifies to

$$\left( 1 - \frac{l(l + 1)}{k^2R^2} \right) \left[ h^{(1)}_l(x) \frac{dh^{(2)}_l(x)}{dx} - h^{(2)}_l(x) \frac{dh^{(1)}_l(x)}{dx} \right]_{x=kR} = 0. \quad (22)$$

The expression in the square brackets is the Wronskian of $h^{(1)}_l(x)$ and $h^{(2)}_l(x)$, and it is not zero, because these two solutions of the spherical Bessel equations are independent. Therefore, from (22) we get $\omega_l = c_0k_l = \frac{c_0}{R} \sqrt{l(l + 1)}$, and in this crude approximation, the Schumann resonance frequencies are

$$f_l = \frac{\omega_l}{2\pi} = \frac{c_0}{2\pi R} \sqrt{l(l + 1)}, \quad l = 1, 2, \ldots \quad (23)$$

The observed frequencies of the first five Schumann resonances are 7.8, 14.1, 20.3, 26.4 and 32.5 Hz, respectively [21], and they are about 25% lower than it follows from (23).

Winfried Otto Schumann, a professor at the Technische Hochschule München, rightfully gets most of the credit for predicting Schumann Resonances. However, Schumann resonance history is an interesting story [22]. The idea of
natural global electromagnetic resonances goes back to George F. Fitzgerald in 1893 and Nikola Tesla in 1905 [22, 23]. The formula (23) for resonance frequencies of a spherical condenser was first obtained by Joseph Larmor already in 1894 [22].

Above we have outlined just some basics of Schumann resonances for the reader’s convenience. More detailed information about Schumann resonance research can be found in books [17, 24, 25, 26, 27].

3. Excitation of Schumann resonances by an asteroid impact

Schumann resonances are excited primarily by lightning discharges. On the other hand, it is known that explosions and hypervelocity impacts are accompanied by macroscopic charge separation [28, 29, 30]. Upon a hypervelocity impact, a partially ionized plasma is formed, which rapidly expands. In addition to plasma, the impact will result in the formation of molten and fragmented debris of the target material, which are expected to become negatively charged when in contact with the plasma, since electrons are much more mobile than ions. The subsequent inertial separation of the positively charged plasma and the negatively charged debris will lead to the separation of charge over macroscopic distances [30].

One can also imagine some other mechanisms of charge separation, for example, those that act during the dust storms [31] and volcanic eruptions [32]. Therefore, we assume that an asteroid impact is immediately accompanied by a thunderstorm with a large number of lightning discharges. Namely, let \( dN(t) = Ne^{-t/T} \) be the number of lightning discharges during a time period \( dt \) at the time \( t \) after the impact. Here \( T \approx 100 \text{ s} \) is the transient crater formation time for the Chicxulub event [33], and \( N \) is the total number of lightning strikes in the impact thunderstorm. If the current in an average individual lightning strike is \( I_0 e^{-t/\tau} \), with \( \tau \approx 500 \mu s \) and \( I_0 \approx 2 \cdot 10^4 \text{ A} \) [34], the total current will be

\[
I(t) = \int_0^t e^{-t/s} dN(s) = \frac{NI_0}{T} e^{-t/T} \int_0^t e^{(t-s)/\tau} ds \approx \frac{NI_0\tau}{T} e^{-t/T},
\]

(24)

where at the last step we have taken into account that \( T \gg \tau \) (in fact, this condition is not sufficient do discard the second exponent \( e^{-t/\tau} \), which occurs after the integration in (24), since short signals with \( \omega_n \tau \sim 1 \) can excite Schumann resonances just as effectively as long signals with \( \omega_n T \gg 1 \).
However, it will be clear from the final answer that we can still neglect the contribution of this term due to the condition $\omega_n \tau \ll 1$, which is satisfied by the first few Schumann resonances.

Accordingly, as the current density, which we will consider having only a radial component, we take

$$j_r(\vec{r}, t) = \frac{I(t) \Delta l}{2\pi r^2 \sin \theta} \delta(\theta) \delta(r - R) \Theta(t),$$  \hspace{1cm} (25)

where $\Theta(t)$ is the Heaviside step function introduced to indicate that there is no current for $t < 0$, and $\Delta l \approx 10^3 \text{ m} \ [34]$ is the length of an average lightning channel. The current density (25), when integrated over the whole space, gives the total current moment:

$$\int j_r(\vec{r}, t) \, dV = I(t) \Delta l.$$

Now we will consider how the Schumann resonances are excited by the vertical electric dipole with current density (25). We will closely follow [24], for other approaches see [26] and [17, 34].

Maxwell equations

$$\nabla \times \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t}, \quad \nabla \times \vec{H} = \epsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{j}(\vec{r}, t),$$  \hspace{1cm} (26)

for Fourier components with $e^{i\omega t}$ time dependence take the form

$$\nabla \times \vec{E}(\vec{r}, \omega) = -i\omega \mu_0 \vec{H}(\vec{r}, \omega), \quad \nabla \times \vec{H}(\vec{r}, \omega) = i\omega \epsilon_0 \vec{E}(\vec{r}, \omega) + \vec{j}(\vec{r}, \omega),$$  \hspace{1cm} (27)

where $\vec{j}(\vec{r}, \omega)$ has only the radial component

$$j_r(\vec{r}, \omega) = \int_{-\infty}^{\infty} e^{-i\omega t} j_r(\vec{r}, t) \, dt = \frac{NI_0 \Delta l \tau}{1 + i\omega T} \frac{\delta(\theta) \delta(r - R)}{2\pi r^2 \sin \theta}. \hspace{1cm} (28)$$

A vertical electric dipole source at $\theta = 0$ can excite only fields that do not have a $\phi$-dependence. This follows from the azimuthal symmetry of the problem. Then it can be checked in spherical coordinates that the fields given by equations (10) still satisfy the Maxwell equations (27) if the Debye superpotential $U(r, \theta)$ satisfies the equation

$$r(\Delta + k^2)U = \left( \frac{\partial^2}{\partial r^2} + k^2 \right) (rU) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial U}{\partial \theta} \right) = -\frac{j_r(\vec{r}, \omega)}{i\omega \epsilon_0}. \hspace{1cm} (29)$$

Since $j_r(\vec{r}, \omega)$ is proportional to $\delta(r - R)$, it vanishes in the Earth-ionosphere cavity. Thus, in the cavity $U(\vec{r}, \omega)$ is still given by (13) with the difference
that only \( m = 0 \) modes are excited due to azimuthal symmetry, and, therefore \( Y_{lm} \) spherical functions can be replaced simply by Legendre polynomials \( P_l(\cos \theta) \):

\[
U(\vec{r}, \omega) = \sum_{n=0}^{\infty} \left[ A_n h_n^{(1)}(kr) + B_n h_n^{(2)}(kr) \right] P_n(\cos \theta). \tag{30}
\]

The boundary condition at \( r = R + h \) is

\[
\left. \frac{\partial}{\partial r} (rU) \right|_{r=R+h} = 0, \tag{31}
\]

if the ideally conducting ionosphere is assumed. To get the boundary condition at \( r = R \), we integrate \[29\] over \( r \) from \( R - \varepsilon \) to \( R + \varepsilon \), take into account that inside the ideally conducting Earth there is no tangential electric field and hence \( \left. \frac{\partial}{\partial r} (rU) \right|_{r=R-\varepsilon} = 0 \), and finally take the limit \( \varepsilon \to 0 \). As a result, we get \[24\]

\[
\left. \frac{\partial}{\partial r} (rU) \right|_{r=R} = -\frac{N I_0 \Delta l \tau}{1 + i\omega T} \frac{\delta(\theta)}{2\pi i \varepsilon_0 \omega R^2 \sin \theta} = -\sum_{n=0}^{\infty} a_n P_n(\cos \theta). \tag{32}
\]

where

\[
a_n = \frac{N I_0 \Delta l \tau}{1 + i\omega T} \frac{1}{2\pi i \varepsilon_0 \omega R^2} \left( n + \frac{1}{2} \right), \tag{33}
\]

and at the last step, we have expanded \( \delta(\theta) \sin \theta \) into a series of Legendre polynomials:

\[
\frac{\delta(\theta)}{\sin \theta} = \sum_{n=0}^{\infty} \left( n + \frac{1}{2} \right) P_n(\cos \theta). \tag{34}
\]

Substituting \[30\] into \[31\] and \[32\], we get the following system of linear equations for unknown coefficients \( A_n \) and \( B_n \):

\[
A_n u_n'(k(R + h)) + B_n v_n'(k(R + h)) = 0,
\]

\[
A_n u_n'(kR) + B_n v_n'(kR) = -a_n. \tag{35}
\]

This system is easily solved, and if the results are substituted in \[30\], we obtain

\[
U = \sum_{n=0}^{\infty} a_n \frac{u_n'(k(R + h)) h_n^{(1)}(kr) - u_n'(k(R + h)) h_n^{(2)}(kr)}{u_n'(k(R + h)) v_n'(kR) - v_n'(k(R + h)) u_n'(kR)} P_n(\cos \theta). \tag{36}
\]
From (12) it follows that the Hankel functions satisfy the relation
\[
\left( \frac{d^2}{dr^2} + k^2 \right) \left( rh_n^{(1,2)}(kr) \right) = \frac{n(n + 1)}{r} h_n^{(1,2)}(kr).
\] (37)

Then from (10) and (36) we obtain the following expression for the Fourier component \(E_r(\vec{r}, \omega)\) of the electric field on the ground (at \(r = R\)):
\[
E_r(\vec{r}, \omega) = \sum_{n=0}^{\infty} \frac{a_n n(n + 1)}{R} c_n P_n(\cos \theta),
\] (38)

where
\[
c_n = \frac{v_n'(k(R + h)) h_n^{(1)}(kR) - u_n'(k(R + h)) h_n^{(2)}(kR)}{u_n'(k(R + h)) v_n'(kR) - v_n'(k(R + h)) u_n'(kR)}.
\] (39)

Now we use, as in the previous section, smallness of the ratio \(h/R\) and expand both the numerator and denominator of \(c_n\) in terms of this small quantity.

To first order, we have
\[
\begin{align*}
u_n'(k(R + h)) & v_n'(kR) - v_n'(k(R + h)) u_n'(kR) \approx kh \left( n(n + 1) - k^2 R^2 \right) W, \\
v_n'(k(R + h)) h_n^{(1)}(kR) - u_n'(k(R + h)) h_n^{(2)}(kR) & \approx kR W,
\end{align*}
\] (40)

where \(W\) is the Wronskian of \(h_n^{(1)}(x)\) and \(h_n^{(2)}(x)\) at \(x = kR\). Replacing \(n(n + 1)\) by \(R^2 c_n^2\) and \(k^2\) by \(\frac{\omega^2}{c^2}\), we get
\[
E_r(\vec{r}, \omega) = \sum_{n=0}^{\infty} \frac{a_n \omega^2 P_n(\cos \theta)}{h(\omega_n^2 - \omega^2)} = \frac{NI_0 \Delta l \tau}{4 \pi i c_0 R^2 h(1 + i\omega T)} \sum_{n=0}^{\infty} \frac{\omega^2 (n+\frac{1}{2}) P_n(\cos \theta)}{\omega_n^2 - \omega^2}. \quad (41)
\]

But \(\frac{\omega^2}{\omega_n^2 - \omega^2} = 1 + \frac{\omega^2}{\omega_n^2 - \omega^2}\), and the first term according to (34) will lead to a \(\delta(\theta)\) proportional contribution that is equal to zero outside the source. Therefore, finally we can write
\[
E_r(\vec{r}, \omega) = \frac{NI_0 \Delta l \tau}{4 \pi i c_0 R^2 h(1 + i\omega T)} \sum_{n=0}^{\infty} \frac{\omega}{\omega_n^2 - \omega^2} (2n + 1) P_n(\cos \theta). \quad (42)
\]

To find the electric field in the time domain, we perform the inverse Fourier transform of the frequency domain field \(E_r(\vec{r}, \omega)\) (since it is assumed that the Earth is perfectly conductive, the electric field on the ground is radial, so we omit the lower index indicating the radial component in \(E(\vec{r}, t)\)):
\[
E(\vec{r}, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i\omega t} E_r(\vec{r}, \omega) d\omega. \quad (43)
\]
However, for the integral (43) to have a well-defined meaning, it is necessary to indicate how to handle the singularities of the integrand: as is clear from (42), we have three simple poles at $\pm \omega_n$ and $i \tau$, and the first two of them lie on the integration contour of (43).

This problem is solved by noting that in reality the Earth and ionosphere are not ideal conductors and as a result the Schumann eigenfrequencies become complex with small imaginary parts $\gamma_n = \omega_n^2 Q_n \ll \omega_n$ [17] (the quality factors for the first Schumann resonances are $Q_1 \approx 4.63$, $Q_2 \approx 5.96$, $Q_3 \approx 6.56$, $Q_4 \approx 6.83$, $Q_5 \approx 6.95$ [17]). For a dissipative ionosphere, the imaginary part $\gamma_n$ of the positive pole at $\omega = \omega_n$ is positive. The imaginary part of the negative pole at $\omega = -\omega_n$ is fixed by the condition $E^*_r(\vec{r}, \omega) = E_r(\vec{r}, -\omega)$ (the reality condition for the time domain field $E_r(\vec{r}, t)$) and turns out to be also $\gamma_n$. Therefore, we replace $(\omega^2 - \omega_n^2)^{-1}$ in the integral (43) by $[(\omega - \omega_n - i\gamma_n)(\omega + \omega_n - i\gamma_n)]^{-1}$, close the integration contour in the upper half-plane where the integrand decreases exponentially, and evaluate the integral according to the Cauchy residue theorem as a sum of residues at three simple poles. As a result, we obtain

$$E(\vec{r}, t) = \frac{N I_0 \Delta l \tau}{4 \pi \varepsilon_0 R^2 h} \sum_{n=0}^{\infty} \frac{(2n+1) P_n(\cos \theta)}{1 + \omega_n^2 T^2} \left[ e^{-\frac{t}{T}} - e^{-\gamma_n t} (\cos \omega_n t + \omega_n T \sin \omega_n t) \right]. \quad (44)$$

The first $e^{-t/T}$ term in square braces expresses the direct, non-resonant contribution to the electric field from the source, while the remaining terms correspond to to the excitation of resonant modes of the cavity [34]. Since $\omega_n T \gg 1$, the resonant part of the electric field takes the form

$$E_{\text{res}}(\vec{r}, t) = -\frac{N I_0 \Delta l \tau}{4 \pi \varepsilon_0 R^2 h} \sum_{n=0}^{\infty} (2n+1) \frac{e^{-\gamma_n t}}{\omega_n T} \sin \omega_n t \quad P_n(\cos \theta). \quad (45)$$

To estimate an average amplitude of the excitation, we replace $e^{-\gamma_n t}$ by its average value $\frac{1}{T} \int_{0}^{T} e^{-\gamma_n t} dt \approx \frac{1}{\gamma_n T}$ [34]. In this way, we get for the amplitude of the first Schumann resonance

$$A_1 \approx \frac{3N I_0 \Delta l \tau}{4 \pi \varepsilon_0 R^2 h \omega_1 \gamma_1 T^2} = \frac{3\Delta Q \Delta l}{4 \pi \varepsilon_0 R^2 h \omega_1 \gamma_1 T^2}, \quad (46)$$

where $\Delta Q = NI_0 \tau$ is the total amount of electric charge separated by a macroscopic distance. In [30] the following empirical relation was obtained
for $\Delta Q$ in laboratory scale hypervelocity impacts (all quantities are in the SI units)

$$\Delta Q \approx 10^{-2} m \left( \frac{V}{3000} \right)^{2.6\pm0.1},$$

(47)

where $m$ is the impactor mass, and $V$ is its velocity. It was argued that the Chicxulub impactor was a fast asteroid or a long-period comet with energy between $1.3 \times 10^{24}$ J and $5.8 \times 10^{25}$ J, and mass between $1.0 \times 10^{15}$ kg and $4.6 \times 10^{17}$ kg. Taking the lowerest numbers $m = 1.0 \times 10^{15}$ kg and $E_{kin} = 1.3 \times 10^{24}$ J, for the velocity we obtain $V = \sqrt{\frac{2E_{kin}}{m}} \approx 50$ km/s. Then an interpolation of empirical relation (47) to this enormous scale gives a huge number $\Delta Q \approx 1.5 \times 10^{16}$ C. However, a recent simulation resulted in the Chicxulub scale impact-generated magnetic field that was three orders of magnitude smaller than expected from the relation (47). Therefore, as a more realistic estimate, we will take $\Delta Q \approx 1.5 \times 10^{13}$ C. As for other parameters in (46), we will assume $R = 6400$ km, $h = 75$ km, $\omega_1 = 49$ and $\gamma_1 = 5.3$. Then we get from (46) the following amplitudes for the electric and magnetic fields of the first Schumann resonance:

$$A_1 \approx 50 \text{ V/m}, \quad B_1 = \frac{A_1}{V_{ph}} \approx 230 \text{ nT},$$

(48)

where $V_{ph} \approx 0.7c_0$ is the phase velocity of the electromagnetic waves in the earth-ionosphere cavity. For comparison, the measured Schumann resonance background fields are very small, of the order of mV/m for the electric field, and several pT for the magnetic field [23]. As we see, estimated magnitudes of the Chicxulub impact induced Schumann resonance fields exceed to their present-day values about $5 \times 10^4$ times.

4. On biological effects of ELF electromagnetic fields

Schortly after Schumann and his graduate student König made their first attempts to detect Schumann resonances, König and Ankermüller noted a striking similarity between these signals and human brain electroencephalograms (EEG) [37].

The classical EEG rhythms are delta (1-3 Hz), theta (4-7 Hz), alpha (8-13 Hz), beta (14-29 Hz) and gamma (30-80+ Hz) [38], and we can try to roughly estimate these fundamental brain frequencies as follows [39].
Human neocortex, which form most of the white matter, contains about $10^{10}$ interconnected neurons. Imagine that the wrinkled surface of each hemisphere, where these neurons are situated, is inflated so that to create a spherical shell with effective radius $a = \sqrt{S/4\pi}$, where $S = 1000 - 1500 \text{ cm}^2$ is the surface area of the hemisphere. Characteristic corticocortical axon excitation propagation speed is $V = 600 - 900 \text{ cm/s}$. Therefore we can write the wave equation for the propagation of these excitation waves on the surface of the sphere as follows:

$$\Delta \Phi(\theta, \varphi, t) = \frac{1}{V^2} \frac{\partial^2 \Phi(\theta, \varphi, t)}{\partial t^2},$$

(49)

where $\Phi$ is some quantity characterizing the excitation. Because of spherical symmetry, we seek the solution of (49) in the form

$$\Phi(\theta, \varphi, t) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} A_{lm} F_l(t) Y_{lm}(\theta, \varphi).$$

(50)

Recalling (11) and taking into account that $r = a = \text{const}$ and $\Delta \perp Y_{lm} = -l(l + 1)Y_{lm}$, we get the following differential equation for $F_l(t)$ after separating the variables:

$$\frac{1}{V^2} \frac{d^2 F_l(t)}{dt^2} = -\frac{l(l + 1)}{a^2} F_l(t).$$

(51)

This is the equation of harmonic oscillations with the cyclic frequency

$$\omega_l = \frac{V}{a} \sqrt{l(l+1)}.$$

(52)

In particular, for the first fundamental frequency we get $f_1 = \frac{\omega_1}{2\pi} = 8 - 18 \text{ Hz}$, which is close to the frequency of alpha rhythm [39].

From how we obtained Schumann resonances and brain waves, it should be clear that the similarities between them are the result of spherical symmetry and the small height of the ionosphere compared to the radius of the Earth. The existence of standing waves requires only that the material medium supports traveling waves that do not decay too quickly. Then the corresponding resonant frequencies are determined from the geometry of the problem and from the boundary conditions. Therefore any similarity between brain waves and Schumann resonances may well be just a coincidence, and for their interconnection a wild stretch of our imagination will be required [40]. Nevertheless, some arguments can be envisaged that these two desperately different phenomena are actually interrelated.
ELF electromagnetic fields and Schumann resonances have been present on Earth since the formation of the ionosphere. Therefore, they accompanied life from the very beginning, and it does not seem too wild to assume that in the course of evolution living organisms have found some useful application to these ubiquitous electromagnetic fields. One can even imagine that the ELF electromagnetic fields and related electric activity in the Precambrian Earth’s atmosphere played the crucial role in the emergence of life according to the following scenario \cite{41, 42}.

In the Precambrian era, the atmosphere of the Earth was much larger and more similar to what Jupiter has today. In addition, the ionosphere was also much farther than today, about $10^3$ km far from the Earth’s surface, in the immediate vicinity of the Van Allen belts. As a result, fluctuations of current in the Van Allen belts were capably of generating huge currents in the nearby ionosphere and the coupling of these currents to the Earth’s metallic core would lead to an enormous and constant electrical activity. It is believed \cite{41}, these electrical discharges were essential for production of amino acids and peptides from which the first living organisms were formed. This process was accompanied by an intense background of the ELF electromagnetic field, which could affect the formation and functionality of the first living cells and organisms.

It has been suggested that these atmospheric ELF background fields played a major role in the evolution of biological systems, especially in the early stages of evolution \cite{43}. In particular, the dominant brain wave frequencies may be the evolutionary result of the presence and effect of this ELF electromagnetic background \cite{44}. This idea is to some extent supported by the amazing fact that many species exhibit, irrespective of the size and complexity of their brain, essentially similar low-frequency electrical activity \cite{43}.

Various remote sensing systems of living organisms, such as visual system or the infrared sensors of snakes, have been developed due to the presence of electromagnetic energy in the corresponding parts of the spectrum. On early Earth, there was a significant amount of electromagnetic energy in the ELF portion of the spectrum. Thus, we can expect that organisms could adapt and somehow use this part of the electromagnetic spectrum too, in particular the Schumann peaks of the Earth’s ELF electromagnetic field \cite{44}. The following observation provides some support for this idea.

Heat shock genes are responsible for adapting organisms to harsh environmental conditions. They are ubiquitous, present in various organisms from
bacteria to humans and represent the most conservative and ancient group of genes. The proteins encoded by these genes (heat shock proteins, HSPs) serve as molecular chaperones, which help in the repair, folding and assembly of nascent proteins during stress and prevent the accumulation of damaged cellular proteins.

It has been experimentally demonstrated that the ELF electromagnetic fields can induce various heat shock proteins and, in particular, HSP70, like a real heat shock. The most surprising fact was that the electromagnetic fields caused the synthesis of HSP70 at an energy density of fourteen orders of magnitude lower than in heat shock [45].

Such extraordinary sensitivity to the ELF magnetic fields (unlike ELF electric fields, magnetic fields easily penetrate biological tissues) should have a good evolutionary basis. Astrophysical simulations show that shortly after the formation of the solar system, giant planets Jupiter and Saturn begin to migrate inward or outward. This planetary migration destabilizes the orbits of Neptune and Uranus into eccentric ellipses. As a result of this, the ice giants begin to cross the planetesimal disk beyond the orbit of Neptune and gravitationally scatter these planetesimals, forcing many of them to go along the Earth-crossing trajectories. The resulting so-called Late Heavy Bombardment (LHB) could have both positive and negative consequences for the emergence of life [46]. In any case, the first living cells are expected to face grave dangers of powerful bombardment by meteorites (LHB tail). Thus, it can be assumed that the cells could use ELF magnetic pulses as a kind of early warning system that gives them time to prepare for other really dangerous stressors such as the heat pulse and the blast wave, which often follow the electromagnetic pulse [47].

However, a very detailed analysis in [48] indicates that, from the point of view of the conventional classical physics, it remains a mystery that very weak ELF electromagnetic fields can cause any biological effect at all. The problem is the thermal noise. If we assume that random electric fields in biological tissues generated by thermal fluctuations of charge densities are correctly described by the Johnson-Nyquist formula, as in ordinary conductors, then the inevitable conclusion is that, for external ELF electric fields weaker than 300 V/m, and for external ELF magnetic fields weaker than 50 µT, it seems impossible to influence biological processes, since any effects generated by such fields in the body will be masked by thermal noise [48]. This objection is known as the kT problem.

Despite of these categorical conclusions, biologists continued the exper-
imental attempts to detect biological effects of ELF electromagnetic fields, remembering the words of Szent-Gyorgyi that "the biologist depends on the judgement of the physicist, but must be rather cautious when told that this or that is improbable" [49].

As a result of these attempts, a diverse and incontrovertible evidence had been accumulated indicating that ELF radiation has important effects on the functioning of cells [50]. We cite only a few reviews of the subject [51, 52, 53, 54, 55, 56], where further references can be found.

The usual formulation of the kT problem is based on several implicit assumptions that are not always justified [57, 58]. For example, the Johnson-Nyquist formula assumes that the system is in a thermal equilibrium. Even so, although a living organism as a whole is very far from thermal equilibrium, the nature of this non-equilibrium is such that the concept of a well-defined temperature nevertheless exists [59]. In fact, the physical nature of the biological effects of ELF fields still remains an enigma, and more work is needed to elucidate the comprehensive mechanisms behind these effects [56, 59].

5. Concluding remarks

As we have seen, the magnitudes of the Schumann resonance fields are expected to increase tremendously after the Chicxulub impact. Nevertheless, this effect will be rather short-lived, since Schumann resonance fields decay rapidly due to low Q-factors of resonances.

In the long run, the impact of this magnitude will cause a very serious enviromental damage. As a result, stratospheric dust, sulfates released as a result of impact, and soot from extensive worldwide forest fires caused by exposure to the impact related thermal radiation, can lead to significant climate changes over decades (impact winter) [61] and hence modify lightning activity, which is the main source of energy for Schumann resonances.

In addition, blast wave for some time distorts the ionosphere and changes the frequencies of Schumann resonances (after high altitude "Starfish" nuclear test explosion, all resonance frequencies abruptly dropped by about 0.5 Hz [27]).

It has been suggested that ELF background atmospheric fields played a major role in the evolution of biological systems, and in particular that Schumann resonances are used for synchronization by living organisms [43, 61]. If so, then the change in the Schumann resonance parameters after the
Chicxulub impact could have a stressful effect, contributing to a devastating load on the global biosphere, including dinosaurs.

A somewhat similar idea can be found in [62], where it was suggested that the influence of the ELF and ultra-law frequency (ULF) electromagnetic fields produced by widespread earthquakes and volcanism in the dinosaur era stimulated their growth in size, and when these phenomena were no longer so common dinosaurs became extinct for a number of reasons, including the loss of intensity of the ULF/ELF electromagnetic fields.

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