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Magnetic factor in solar-terrestrial relations and its impact on the human body: physical problems and prospects for research

T K Breus, V N Binhi, A A Petrukovich

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Contents

Abstract. **The body of current heliobiological evidence suggests that very weak variable magnetic fields due to solar- and geomagnetic-activities do have a biological effect. Geomagnetic disturbances can cause a nonspecific reaction in the human body — a kind of general adaptation syndrome which occurs due to any external stress factor. Also, specific reactions can develop. One of the reasons discussed for the similarity between biological and heliogeophysical rhythms is that geomagnetic variations have a direct influence on organisms, although exact magnetoreception mechanisms are not yet clear. The paper briefly reviews the current state of empirical and theoretical work on this fundamental multidisciplinary problem.**

Keywords: geomagnetic disturbances, biological and geomagnetic rhythmicity, mechanisms of magnetoreception, magnetobiology

1. Introduction

Our fellow countryman Aleksandr Leonidovich Chizhevskii is widely recognized as the founding father of heliobiology and research on the influence of solar activity on Earth's biosphere. He showed in the first third of the 20th century that epidemic diseases and social upheavals, variations in the crop yield, and unaccountable surges of cardiovascular mortality correlate with solar activity (the number of sunspots) [1]. Chizhevskii argued that "simultaneous periodic changes in solar and human activities give incontestable evidence of their physical relationship." His theory left an indelible mark on the history of science, even though some of his conclusions were not confirmed by later studies. Since then, belief in the influence of solar activity on human health has become an essential element of the public conscience.

In only a few decades (the 1950s–1960s), the first space flights brought the discovery of Earth's magnetosphere (the magnetic envelope of our planet) and the solar wind (a flux of plasma from the solar crown with the interplanetary magnetic field affecting the magnetosphere). Characteristic features of this impact are, for example, geomagnetic variations (disturbances) and northern lights regularly, almost every day, observed in polar regions. Solar activity also manifests itself in the form of solar flares and coronal holes, as well as sudden enhancement of the solar wind leading to such global perturbations as geomagnetic storms. Variations of the geomagnetic field are paralleled by enhanced electromagnetic noise of ionospheric origin in different frequency ranges, infrasound fluctuations in Earth's atmosphere, plasma energy pouring into the atmosphere, etc. [2]. Magnetic storms are often described in terms of intensity of geomagnetic perturbations (geomagnetic activity, GMA).

The Kp-index most frequently used to estimate GMA is a maximum amplitude of the horizontal component of the geomagnetic field within a three-hour interval expressed on a 9-point logarithmic scale and averaged over several geomagnetic observatories located at middle and moderately high latitudes. Kp in excess of 4 points corresponds to a geomagnetic storm. Another GMA index, Dst, characterizes the maximum deviation of the magnetic field from the undisturbed state at four magnetic stations in equatorial latitudes. A Dst-index below -50 nT gives evidence of a moderate geomagnetic storm.

The amplitude of fluctuations of the geomagnetic field during storms is on the order of 1000 nT in the polar regions of Earth and 100 nT at its middle and low altitudes, where the geomagnetic field ranges 30,000–50,000 nT (Fig. 1) [3].

Since the geomagnetic variations are small compared with the total field and technogenic noises (as is the case with other physical factors), the mechanisms behind the influence of weak fields on biological objects remain unclear, while

T K Breus, A A Petrukovich Space Research Institute,
Russian Academy of Sciences,
ul. Profsoyuznaya 84/32, 117997 Moscow, Russian Federation
E-mail: breus36@mail.ru, apetruko@iki.rssi.ru
V N Binhi Prokhorov General Physics Institute,
Russian Academy of Sciences,
ul. Vavilova 38, 119991 Moscow, Russian Federation
E-mail: binhi@kapella.gpi.ru
Lomonosov Moscow State University, Faculty of Biology,
Leninskie gory 1, str. 12, 119991 Moscow, Russian Federation

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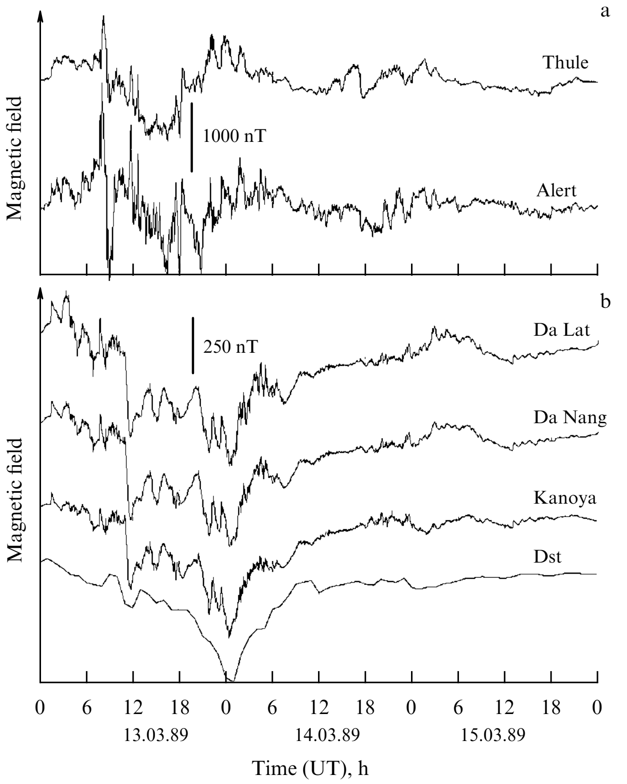

Figure 1. Magnetograms of the horizontal component of the geomagnetic field in a polar region (Thule and Alert) (a), in an equatorial region (Da Lat and Da Nang), at mid-latitudes (Kanoya), and Dst variations (b) during the period from 13 to 15 March 1989 [3].

statistical studies did not always yield consistent and reproducible results. This accounts for the serious skepticism toward heliobiology that arose in the 1970s.

At the same time, modern research based on the computer analysis proved conclusively a significant correlation between geomagnetic disturbances and various characteristics of biological objects or the human body at different levels of organization. "If this relationship at the beginning of heliobiological research could seem (at least for his contemporaries) to have a tinge of physiophilosophy, now it is totally bereft of mysticism: heliobiology has become a natural science discipline with a well-developed methodology based on experiment" (from the Foreword to Ref. [1] by L M Zelenyi).

Generally speaking, the following basic hypothesis, in whose favor the results of numerous studies tell us and to which we shall refer in what follows, can be formulated: (1) the main factor of GMA impact has to do with fluctuations as such of the geomagnetic field; (2) its influence is rather weak compared with other effects (weather factors, stress, etc.), and (3) manifestations of its action on the human body are highly individual and usually unspecific, akin to adaptive stress characteristic of any other external factors. Section 2 briefly surveys the results of statistical studies, and Section 3 includes a review of experimental and theoretical research on potential mechanisms underlying the influence of magnetic fields on living organisms.

2. Comparison of heliogeophysical and biological data

A comparison of the general periodicity of heliogeophysical and medical data provided a first illustration of their possible relationship [4–6]. Time series of GMA exhibit rhythms (i.e., have peaks in frequency spectra) at periods characteristic of the solar rotation period and its harmonics: $\approx$ 28, 14, 9, 6.8, 5.4, 4.5 days, etc. (Fig. 2a). Meanwhile, the existence of similar infradian rhythms, i.e., rhythms with a period longer than 24 h (including a near-seven-day rhythm), in humans has been known since the classical period from the characteristic times of exacerbation of various diseases (see Ref. [6] for details) and from current data on the implant rejection rate following kidney and heart transplantations (Fig. 2c) [4, 6].

This rather simple observation provided a basis for a hypothesis about the influence of GMA on biological objects in terms of biorhythms. The periodicity of such external factor as geomagnetic variations might have been responsible, at earlier stages of evolution, for the development of similar rhythmicity in biological objects, while its disturbance by the irregular aperiodic constituent of GMA (magnetic storms) could cause biological rhythm desynchronosis similar to circadian desynchronosis experienced after transcontinental flights (jet lag). The Moon's orbital motion is also affected by roughly 28-day cycle, but it is difficult to imagine disorders in the periodicity of lunar effects.

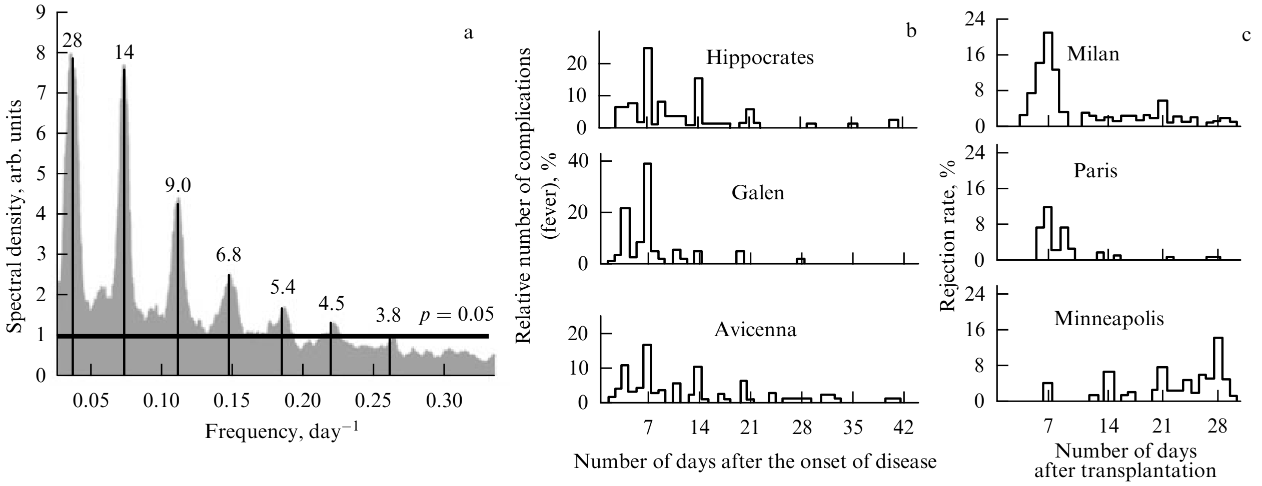

Figure 2. (a) Kp variation spectrum for 28 years (1968–1996); p is the probability of error (rejecting a true null hypothesis). (b) Fever prevalence rhythms calculated from the protocols of ancient physicians. (c) Implant rejection rhythms following kidney and heart transplantations [4, 6].

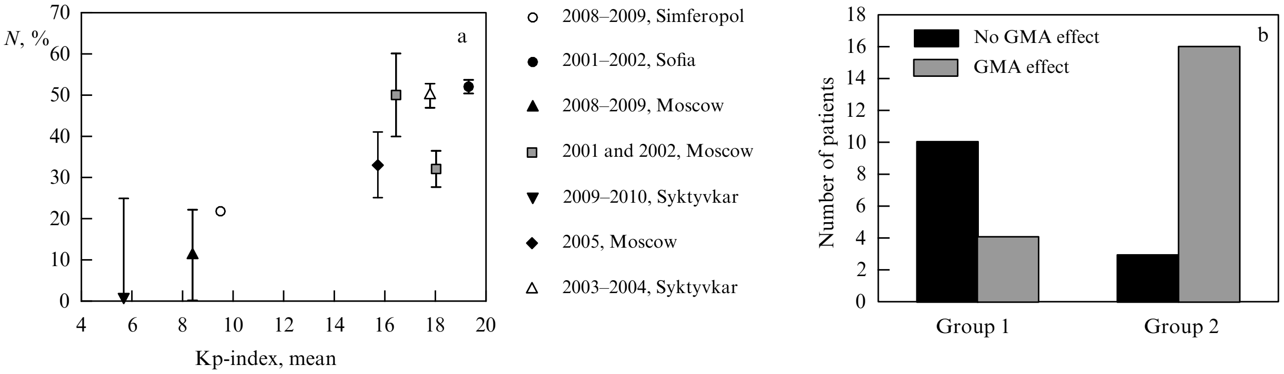

Figure 3. (a) Magnetosensitivity of healthy volunteers [17]. (b) Magnetosensitivity of patients with a hypertensive disease: group 1 — mild hypertension, and group 2 — severe disease [14].

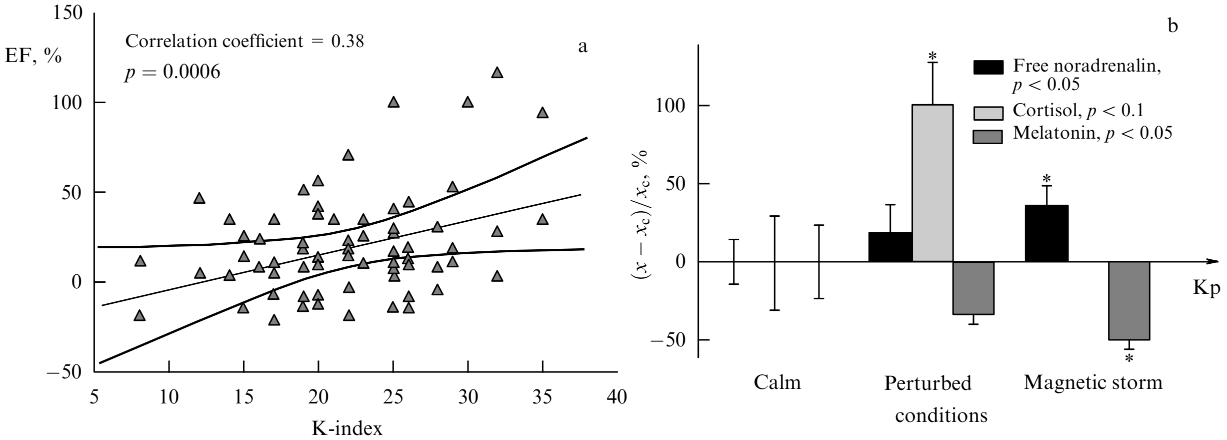

Figure 4. (a) K-index dependence of vascular tone (EF — endothelial function) [21]. Triangles — observations under certain weather conditions; the curves correspond to a 5% confidence interval of an averaged relative EF value over the K-index. (b) Variations in the production of hormones of the sympathoadrenal system (noradrenalin, cortisol) and epiphysis (melatonin) in patients with coronary heart disease and hypertensive disease under perturbed environmental conditions and geomagnetic storms compared with production of the same hormones during a calm geomagnetic period; x are current values; x_c are values under calm geomagnetic conditions. Asterisks (∗) denote significant differences.

The lack of detailed knowledge of the mechanisms underlying geomagnetic variations makes empirical investigations with the help of correlation and regression analyses the main instrument for the evaluation of their influence on physiological processes. Due to relatively weak effects of geomagnetic variations compared with those of other, e.g., social and meteorological, factors, the signal-to-noise ratio sought in the time series being studied is essentially below unity, which accounts for rather low correlation coefficients and the high sensitivity of results to predominant noise characteristics; this implies the necessity of special attention to data choice and processing.

Currently, a wide choice of data is available for analysis, such as many-year medical statistics of major pathologies [7–14], results of long-term monitoring of physiological characteristics of some test patients [7, 8] including astronauts [15], and clinical and laboratory studies of ill and healthy people [16]. The authors of a great amount of research have arrived at the conclusion that the action of weak geomagnetic fields on biological objects is an indisputable fact. A few examples are provided below.

Figure 3a depicts the number of 'magnetically sensitive' (i.e., exhibiting a statistically significant correlation among Kp-index, arterial pressure, and heart rate) healthy volunteers underwent medical surveillance in different regions of the northern hemisphere [cities of Simferopol, Moscow, Syktyvkar (Russia), Sofia (Bulgaria)] [17]. Each study group comprised 16-60 subjects examined separately in the years of minimal (2008-2010) and maximum (2001–2005) solar and geomagnetic activities. Magnetic sensitivity increased with increasing Kp. When its total daily value was higher than 15, the fraction of significant correlations in the study groups amounted to 60%.

Figure 3b shows the number of patients whose arterial pressure significantly correlated with geomagnetic activity. A total of 33 patients treated for hypertensive disease at the A L Myasnikov Research Institute of Cardiology in 2001–2003 were allocated to two groups [14]. Some of them exhibited mild hypertension (group 1), others suffered from multiple cardiac disorders (group 2). Most magnetosensitive patients (80%) fell into group 2, whereas group 1 included only 20% of them. In other words, sensitivity to the geomagnetic factor increased in subjects with serious cardiovascular problems. To recall, the effectiveness of treatment of arterial hypertension remains in spite of the progress made generally rather low. Only 12–30% of patients respond to therapy with a reduction in elevated blood pressure to the target level [18]. There are many factors making it difficult to reach the ultimate goal of hypotensive and antianginal therapy; among them are meteo- and magnetosensitivity [19, 20].

Figure 4a illustrates the K-index dependence of vascular tone (characterized by the endothelial function (EF) and measured in percent [21]) in healthy volunteers (10 practically healthy subjects) observed in the Research and Clinical Center, Russian Railways joint stock company, over 1.5 years. It turned out that the dependence on the geomagnetic index manifests itself largely under favorable weather conditions (temperature above 6 °C, atmospheric pressure below 770 mmHg, and humidity over 38%).

Figure 4b illustrates relative variations in the production of certain hormones during geomagnetic storms and geomagnetically calm periods in patients with coronary heart disease and hypertensive disease. The study was carried out at I M Sechenov First Moscow Medical University and included 22 patients. The levels of the adrenal gland hormones cortisol and noradrenalin (stress hormones) as well as the epiphyseal hormone melatonin proved to undergo the most conspicuous changes [22, 23]. Melatonin is known to be an adaptogen and immunomodulator involved in regulation of circadian rhythms; its level changes during geomagnetic storms, and its deviation from the normal value results in circadian desynchronosis.

A 30% rise in cortisol production and a 30% decrease in thyroid hormone liberation into the blood under perturbed geomagnetic conditions were documented in an experiment conducted by researchers at the Institute of Physiology, Ural Branch of the Russian Academy of Sciences, at the northernmost point of land on Earth, the Svalbard archipelago, with the participation of 980 healthy volunteers [24].

Taken together, the results of numerous studies indicate that geomagnetic perturbations can induce a nonspecific response in the human body in the form of the adaptation syndrome developing under the effect of any extraneous stress factors. Equally possible is a specific reaction resembling the meteotropic one and associated with alteration of vascular tone. GAM is not a direct cause of the disease: it either provokes it or exacerbates the ongoing pathological process and, therefore, may be responsible for serious consequences. Healthy people with enhanced meteosensitivity may experience functional disorders influencing the quality of life. In this event, the concrete dynamics of physiological characteristics differs in individual subjects.

3. Physical problems and mechanisms

3.1 Subject matter of magnetobiology

Natural electromagnetic fields are very low in comparison with technogenic noises and seem to be too weak to affect biochemical processes in living systems. Nevertheless, the possibility of the action of weak magnetic fields should not be disregarded, and not only in the heliobiological context. For example, migrating birds are known to navigate using Earth's magnetic field. Most of the world's population is chronically exposed to the ever-increasing background power-frequency field. These and related phenomena constitute the subject matter of magnetobiology as a branch of biophysics.

The extensive development of magnetobiology began in the 1960s with the advent of the first generators of millimeter wavelength radiation. It was revealed that it could induce a biological reaction [25]. Low-frequency modulated microwaves proved especially active. Soon, it was demonstrated that a modulating signal in the form of a low-frequency field as weak as a geomagnetic one can act on living organisms and, specifically, on oncogenic processes. On the one hand, such action had initially seemed impossible, because biological tissues are diamagnetic and induction currents are vanishingly small. On the other hand, even the slightest chance to observe a nonthermal effect of low fields had looked meaningful.

Neither national nor international programs of magnetobiological research had great success [26]. The authors failed to determine conditions for reliable control over the rise in magnetobiological effects. The problem remains to be solved, even though a wealth of relevant observational and experimental data has been collected.

Magnetobiology deals with several preferred directions of research that have until recently been regarded as weakly related to one another. Table 1 presents their main characteristics, including reproducibility of results, the degree of definiteness in the search for the 'target' experiencing magnetic field action, the field strengths, and the main journals (fields of science) publishing the data obtained.

So-called magnetic navigation in animals appears to be the most representative area of research from the scientific standpoint. It has been shown that many seasonal migrants among wild animals can navigate by Earth's magnetic field (around 50 μT) during their migrations (see, for instance, review [27]). The ability to detect the geomagnetic field in itself is insufficient to search for a good habitat; animals are supposed to be capable of feeling not only the horizontal component of the field but also its vertical constituent [28] or another pair of characteristics, such as its strength and inclination. This would be enough to unambiguously determine the geographic coordinates due to unique features of Earth's magnetic relief. Some animals demonstrate their 'map sense' by perceiving 15–30 nT magnetic fields [29]. The ability to navigate by Earth's magnetic field is either inherent in or can be acquired by birds [30], amphibians [31], turtles [32], and other animals [33].

Reproducibility of animal experiments is, on the whole, acceptable (see, e.g., Ref. [34]). The targets for the magnetic

Table 1. Structure of magnetobiological research.

Characteristic	Laboratory magnetobiology	Magnetic navigation in animals	Epidemiology of electromagnetic fields	Heliobiology
Reproducibility of results	Discrepancy of estimates	Normal	50/50	50/50
Target of magnetic field	Unknown	Stated	Unknown	Unknown
Minimal magnetic fields	20 nT	15 – 30 nT	300 nT	1 – 1000 nT
Number of publications	30,000 – 40,000	4000 – 7000	300 – 500	1000 – 1500
Journals	*Bioelectromagnetics,* *EM Biol. Medicine,* *Bioelectrochem. Bioenerg. ...*	*Nature, Science,* *Phys. Rev., Biophys. J. ...*	Mostly medical journals	*J. Atm. Sol.-Terr. Physics,* *Adv. Space Res.,* *Life Sci. Space Res. ...*

field action are believed to be either magnetic nanoparticles accumulated around nerve fibers [35–37], biradicals of retinal cryptochromes [38, 39], or a synergism of nanoparticles and biradicals [40].

The concrete mechanisms of these phenomena remain unclear, because each of them is difficult to interpret from the physical standpoint. The obscure microscopic mechanism of magnetoreception poses a major challenge in itself, regardless of the behavioral habits of migrating animals.

Elucidation of the general physico-chemical basis of magnetoreception is a realm of laboratory magnetobiology studying reactions of various animate objects — from biochemical systems and individual cells to whole organisms and their groups, with the purpose of identifying biochemical messengers involved in magnetoreception at its early stages. Therefore, the main characteristics to be measured are concentrations of various substances in the organisms and their rates of change.

The reproducibility of results of laboratory magnetobiology leaves much to be desired. An experimental finding depends on a variety of controllable and uncontrollable physico-chemical and physiological factors. Their intricate interactions make agreement between observed and expected results or theoretical predictions just a matter of experimental luck, a find of researchers. In most cases, exposure to a magnetic field produces nonspecific random biological effects of less than 10–15%, making independent replication of the experiment by different research teams difficult. For example, the action of a magnetic field on the activity of melatonin, a hormone involved in regulation of immunity and the ability of humans to develop cancer resistance, was investigated in more than 10 laboratories. Only half of them reported statistically significant effects [41].

Biological reception of 1000-nT fields is an established fact. Certain research groups observed the action of magnetic fields of a few dozen nT on various processes in amino acid solutions [42]. However, the relationship between these observations and other *in vitro* biochemical reactions with *in vivo* magnetobiological effects remains dubious [43]. There is direct evidence of biological action of those low fields as well [44, 45], but such observations are few. Only some 100 reports contain data on amplitude and frequency selectivity of magnetic effects (see the review in book [46]). Evidently, this is not sufficient for a definite conclusion about the physical nature of the phenomenon.

Magnetic effects so elusive on a small spatio-temporal scale under laboratory conditions and therefore barely noticeable in biological fluctuations must be well apparent on a globally averaged scale, e.g., effects of chronic actions on the populations. Under such observation regimes, all variations unpredictable on a small scale are reduced to a minimum. These issues are dealt with in epidemiology of electromagnetic fields [47], including standardization of safe exposition regimes in such fields [48, 49]. The main problem in this context consists in the correct choice of a control sample hampered by the strong influence of other population-related factors on statistics (exposure levels and morbidity rates correlate with social factors).

Based on scores of epidemiological studies and their meta-analyses, the International Agency for Research on Cancer (IARC) classified some electromagnetic fields, such as power-frequency fields in excess of 300 nT [50] and cell phone fields [51], as possibly carcinogenic to humans.

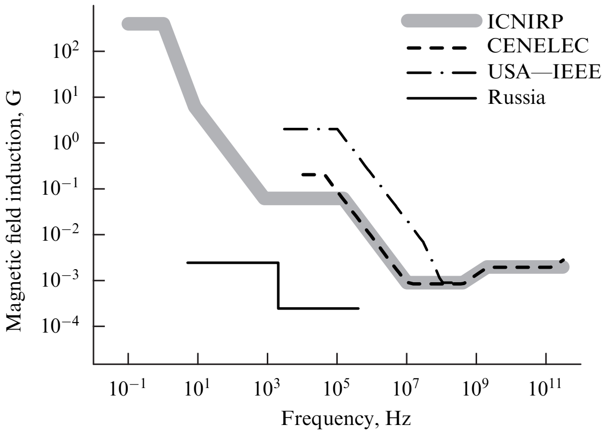

Figure 5. Maximum allowable levels of population exposure to the magnetic component. Solid line — values specified in Russian Sanitary Standards and Regulations (SanPiN 2.2.2/2.4.1340-03), ICNIIP — International Commission on Non-Ionizing Radiation Protection, IEEE — Institute of Electrical and Electronics Engineers, and CENELEC — Comité Européen de Normalisation Électrotechnique.

A special problem is posed by the discrepancy between the existing electromagnetic safety standards adopted in different countries and organizations. The difference in certain frequency ranges amounts to 3–4 orders of magnitude (Fig. 5). This situation reflects the poor understanding of magnetoreception mechanisms and risks associated with chronic exposure to a slowly changing magnetic field (of a magnetic storm type) or magnetic vacuum (a permanent field much smaller than the geomagnetic field).

Numerous facts of biological reception of nanotesla-level fields in the first two areas of magnetobiology (see Table 1) are also confirmed by observations of heliobiological correlations. As follows from Sections 1 and 2, most of them have the form of correlations between geomagnetic perturbations (an integral factor of solar–terrestrial relations) and indicators of the state of higher organisms. These correlations do not prove a direct action of ultralow fields, nor do they exclude it. Interestingly, studies of correlations between geomagnetic disturbances and navigation abilities of birds in terms of direct action date back to the 1950s [52]. Today, researchers still consider these correlations in terms of direct action.

3.2 Possible physical mechanisms of magnetoreception

Failing to obtain a satisfactory explanation of magnetoreception for the last 30–40 years, researchers have to resort to deductive reasoning through 'first principles' in an attempt to elucidate the primary reception mechanism.

The main facts about magnetobiology are fairly well known: (1) biological effects may occur in fields capable of exerting vanishingly small thermal and inductive actions; (2) biological effects are nonlinear: they may comprise the falling sections in the growing magnetic field [53], and (3) biological effects are difficult to predict. The first fact (the so-called 'kT problem') is really surprising. It can be expressed by the inequality $mH \ll kT$, where H is the field strength, m is the magnetic moment of the putative target, k is the Boltzmann constant, and T is the effective temperature of the target. The electron magnetic energy, e.g., in the geomagnetic field, is equal to 2.9×10^{-9} eV, or seven orders of magnitude lower than kT at physiological temperatures.

It remains unknown how changes in magnetic energy smaller than the scale of thermal fluctuations influence chemical reactions (such an influence is necessary to induce a biological response). In other words, the correct explanation implies conversion of the above inequality into at least an approximate equality.

One of the plausible hypotheses maintains that the target has a large magnetic moment. For example, magnetic nanoparticles may naturally arise in organisms or get into them from outside. This conjecture would resolve the problem [54]. However, nonthermal effects occur just as well in organisms *a priori* having no magnetic nanoparticles, stimulating the search for molecular magnetoreception mechanisms. The simplest microscopic single-particle systems are most frequently considered (e.g., a charged oscillator or rotator, spin magnetic moment).

It has to be assumed for the presence of a molecular magnetoreception mechanism, i.e. for overcoming the aforementioned inequality, that the effective temperature of the target is low. This is possible only if dissipation effects arising from the interaction between the dynamical system and the thermostat are small. Dissipation can be neglected if the evolution of relevant degrees of freedom is completed before thermal equilibrium is reached, i.e., if the lifetime of these degrees is shorter than their thermal relaxation time. Such degrees of freedom are well known, e.g., intermediate spin-correlated states of radical pairs in magnetochemical reactions.

However, dissipation is not the sole cause preventing reliable transformation of the magnetic field signal into a change in the chemical reaction rate. Another interfering factor is inertia: the finite change in the generalized coordinate velocity does not occur immediately upon the application of force but is a linear function of time. Accordingly, energy and coordinate change are proportional to t^2. Under the most favorable conditions, the energy of a particle with elementary charge and mass acquires (at small magnetic forces typical of magnetobiology) the kT level after an unrealistically long time even in the absence of dissipation.

Do inertialess mechanisms exist at all? Yes, they do; they are based on consistent patterns of the angular momentum dynamics and quantum phase. The finite angular velocity of free precession develops as soon as the torque is applied and shows no explicit time dependence due to degeneracy of the energy of rotation in the direction of the momentum, which means that the direction of the angular momentum is possible to change in proportion to t, i.e., in an inertia-free mode. A similar situation takes place for the quantum phase unrelated to the quantum particle energy.

Inertialess hypothetical molecular magnetoreception mechanisms are the most perspective and extensively discussed. They imply the influence of a magnetic field on (a) the rate of reactions involving spin-correlated radical pairs [55, 56], (b) quantum rotations of molecular groups inside proteins [57, 58], and (c) local spin and structural order in liquid water [59–62]. A detailed analysis of many quantum mechanisms including those associated with the Zeeman effect can be found in Ref. [46].

Despite the long history of discussion of all these macroscopic and microscopic magnetoreception mechanisms, none of them nor the primary target has been identified in experiment. The fact is that the results of theoretical calculations as a rule depend on a large number of parameters and are difficult to relate to experimental observations; hence, the importance of more general models that must be an indispensable component of specific biophysical mechanisms of reception of weak magnetic fields.

One such model [63] considers nonuniform precession of the magnetic moment in a magnetic field varying in strength but not direction. Such a field does not cause quantum transitions, and a classical model of Larmor precession is relevant. This precession regime has features comparable to the observed magnetoreception properties. In a series of consecutive stages of magnetic field signal transformations, this previously unknown purely physical stage precedes any biophysical or biochemical mechanism and in many respects determines nonlinear and spectral properties of a biological response. Objects in biological cells having a magnetic moment are represented by unpaired electrons, paramagnetic ions, protons, and other magnetic nuclei. Protein-bound ions and rotations of molecular groups with a distributed charge can have a virtual magnetic moment.

The mechanism being considered involves the following statements: an external field acts on the magnetic moment, and the magnetic moment precesses and undergoes thermal relaxation. The biological effect appears if an appreciable perturbation is introduced into the magnetic moment dynamics for relaxation or a shorter time. The measure of perturbation is a deviation of magnetic moment precession from unperturbed uniform precession in the geomagnetic field. Idealizations of the mode include: (1) uniform precession — the natural background against which microscopic events proceed in living organisms; (2) events at the next level (biophysical or biochemical events in the target) give rise to an inhomogeneous Poisson process, the rate of which periodically depends on the phase of precession in the local system of target coordinates, and (3) a biological event is associated with perturbations of magnetic moment precession of a single type averaged over time and ensemble of randomly oriented local systems of coordinates. Certainly, the biological effect becomes apparent only if changes at the biophysical level pass through the stages of transformation at the biochemical, physiological, and systemic biological levels.

The averaged probability of biophysical events — its dependence on the magnetic field for $\beta\tau < 1/4$ — has the following approximate form in the framework of a given scenario [63]:

$$P(H,h) = \beta\tau - \frac{1}{2}\beta^2\tau^2 - \frac{1}{4}\beta^2\tau^2 \sum_n \mathrm{J}_n^2\left(\frac{\gamma h}{\Omega}\right) \operatorname{sinc}^2\left[\frac{(\gamma H - n\Omega)\tau}{2}\right], \qquad (1)$$

where J_n is the n-order Bessel function, and $\operatorname{sinc} x = x^{-1}\sin x$. This relation connects six minimally necessary variables. Three of them are parameters of the magnetic field, viz. its constant component H, amplitude h, and frequency Ω of the variable component. Three others are the gyromagnetic ratio γ and parameters τ (relaxation time) and β describing, respectively, thermal and 'signal' interactions of the magnetic moment with the immediate environment.

The effects from a permanent magnetic field, in particular, the 'magnetic vacuum' effect, as well as the alternating field effects, $P(H,h) - P(H,0)$, are directed oppositely and can be separated as described by the second and first cofactors under the summation sign in Eqn (1), respectively. An alternating field produces the greatest effect when its frequency is

$\Omega = \gamma H$. In such a case, the amplitude dependence is proportional to $J_1^2(h/H)$; this relation is sometimes obtained in experiment.

This physical mechanism does not rule out concrete molecular biophysical mechanisms of magnetoreception, but is an indispensable component of any such mechanism.

It follows from relation $\Omega = \gamma H$ that neither the amplitude nor the frequency are altogether arbitrary; they need to be chosen in conformity with the gyromagnetic factor of targets of the same type to observe the magnetic effect. Other targets with a gyromagnetic factor diverse from $\gamma = \Omega/H$ remain unperturbed at such a combination of frequency and amplitude. Conversely, all targets in a 'magnetic vacuum' at $H = h = 0$ become perturbed regardless of their gyromagnetic factor as follows from formula (1). The magnetic vacuum is a set of conditions (e.g., in future interplanetary flights) defined in comparison with those under which h and/or H are significantly higher than $1/(\gamma\tau)$; in many experiments, their values vary from 100 to 1000 nT. In other words, there are many more chances to experimentally observe the magnetobiological effect in a hypomagnetic field $h < H < 1/(\gamma\tau)$ than in a permanent–alternating one, even at an optimal Ω-to-H ratio. It can be concluded that the probability of an undesirable reaction of an organism exposed to the magnetic vacuum in a long-term space flight is, for purely physical reasons, much higher than during a magnetic storm on Earth.

The kT problem focuses attention on the incompatibility of the target magnetic energy and thermal perturbation scale ($mH \ll kT$). This means, as far as molecular targets are concerned, that the target's effective temperature is rather low, i.e., thermal relaxation time τ is large. It follows from Ref. [63] that marked effects in excess of several percent arise for $\gamma H\tau > 0.1$, i.e., at rather large τ, in agreement with the condition for overcoming the kT problem. Are targets with large τ realistic? It was predicted in Ref. [64] theoretically that if the biradical mechanism (see, e.g., review [56]) has anything to do with the capacity for magnetic navigation and its 'switching off' in a weak alternating field, there must be electron spin states in the organism with unbelievably high large relaxation times on the order of 0.1 ms. The authors of Ref. [29] estimated, based on the observable sensitivity of bird magnetoreceptors underlain by the same mechanism (15 nT), that τ is roughly 10 μs. In fact, they propose simply disregarding the kT problem rather than searching for its solution by accepting the high value of τ as a given. Such large relaxation times of magnetic moments of magnetoreceptors, if confirmed, would allow heliobiological correlations in terms of the direct action of magnetic field variations to be discussed.

Large τ also follows from a comparison of formula (1) with the data from Ref. [65]. However, the authors of the current article do not insist on the reality of such states, seeing the possibility of hypersensitivity in the framework of more moderate assumptions.

It is worthwhile to note that the kT problem in the form of the aforementioned inequality does not include a most important variable, i.e., time, at variance with the generally accepted model of detecting a weak noisy signal. This opens up one more prospect for the solution to the hypersensitivity problem related to the search for such biophysical structures or organism characteristics extraneous to the primary target, in which small changes may accumulate up to a level distinguishable by biological discriminators.

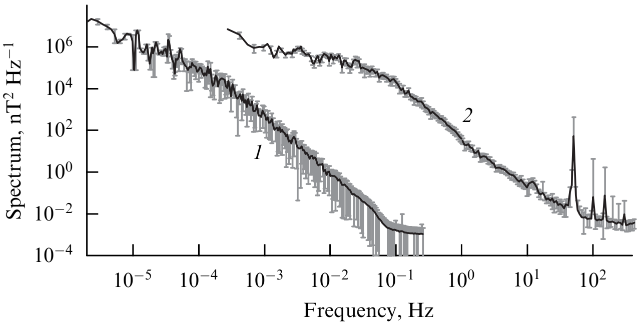

Figure 6. Spectral power density of variations of natural (*1*) and technogenic (urban) (*2*) sources of magnetic noise [46].

A few options for action of the proposed general and other magnetoreception mechanisms are especially relevant to the heliobiological issue. They are specific for the $h \ll H$ regime with respect to the case of $h = 0$.

An interesting possibility takes account of the target's intrinsic molecular rotations observed, for example, when the target is bound to an RNA chain rotating during protein synthesis. Reference [66] considers a model differing from the above one only in that quantum phases or target density of states, instead of the magnetic moment, rotate in a magnetic field. It was shown that the amplitude dependence of the probability of biophysical events is close to the function $J_1^2[h(H - \Lambda/\gamma)^{-1}]$, where Λ is the target's intrinsic rate of rotation. The maximum magnetic effect is reached here at $h \sim H - \Lambda/\gamma$. If rate Λ is close to γH, an effect analogous to that of a magnetic vacuum is feasible for alternating fields with amplitude $h \ll H$. The effect disappears in the geomagnetic field as H (h in the case under consideration) increases. However, this mechanism is inapplicable directly because effective frequencies $\Omega/(2\pi)$ are of order 10 Hz, far from the geomagnetic storm spectrum (Fig. 6), even for rotations of amino acids with a large mass M and $\gamma \sim e/(Mc)$. Another models taking into account the quasistatical and random character of these perturbations need to be developed.

The reception of magnetic fields on the order of several dozen nT was also considered in the framework of the nonmolecular mechanism [67], when a magnetic nanoparticle undergoes stochastic rotations in the two-well potential created by cytoskeletal filaments. It was shown that a magnetic field can alter the height of the barrier. The level of the minimal magnetic fields was calculated to be 100–200 nT. These fields are likely to influence, due to the exponential dependence of the probability of nanoparticle transitions on the barrier height, the frequency of transitions of an arbitrary-standard nanoparticle and thereby induce a biological response.

It is difficult to comment on the incompatibility of the amplitude of geomagnetic variations allegedly detected by living organisms and the much higher level of urban magnetic noise (see Fig. 6). Direct biological action of urban electromagnetic noise appears to be confirmed [45]. We believe the basic fact is the spectra of urban magnetic noise and geomagnetic nose are shifted by two–three orders of magnitude relative to each other. The low-frequency magnetic noise is largely due to geomagnetic perturbations, whereas the urban noise occurs in the higher-frequency range. How does an organism process magnetic noise signals?

Several stages or levels are distinguishable in the overall picture of excitation of a magnetobiological effect. A change

Figure 7. Arfa (a) and Faraday (b) magnetic exposure systems installed at the Research and Clinical Center of the Russian Railways joint stock company, Moscow.

in the state of the primary biophysical target leads to changes in concentrations of biochemical intermediate agents that, in turn, cause changes at the level of individual systems and thereafter at the behavioral level of the whole organism.

Suppose that the magnetoreception system of the organism includes a certain integrator at the pathway of a magnetic field signal having the integration time constant commensurate with the time needed for a magnetic storm to develop (from a few to 24 hours). The urban noise signal at the exit from such integrator would be markedly attenuated, in contrast to the very large integral of the signal of geomagnetic noise. Does the organism have such an integrator? It seems that concentrations of various signal indicators and regulators characterized by low biosynthesis and decomposition rates change sufficiently slowly. Biochemical processes can be exactly such integrators averaging and cumulating the actions of weak factors.

One more difficulty is to explain how weak chronic magnetic signals are differentiated from strong and faster signals. The nonlinear relationship between magnetic moment dynamics and biophysical events of the next level considered earlier in this review probably plays a role. It may be responsible for $J_1^2(x)$ type dependences: namely, the maximum effect is achieved at $x \sim 1$ and then decreases with further increasing and averaging of x.

4. Conclusion

Currently available heliobiological data collectively give evidence of the reality of biological action of very weak alternating magnetic fields of cosmic origin. Sensitivity to magnetic fields of a few dozen nT and higher is reported in other research areas too, e.g., in studies of the magnetic navigation of animals. For all that, the primary target ('receiver') of magnetic fields in organisms remains to be identified, and all mechanisms proposed thus far are purely hypothetical. Magnetic effects depend not only on the parameters of the external field and physical surroundings but also on a great variety of biochemical and physiological factors, making them difficult to predict and reproduce; the magnitude of observable reactions mostly does not exceed 10–15%.

In our opinion, the direct way to solve the problems in question is to conduct extensive interdisciplinary investigations into the biological and medical effects of a magnetic vacuum with a controlled 'depth'. Such an approach would not only provide a wealth of physical information about intracellular microscopic targets of a magnetic field but also allow reducing risks associated with the exposure of the organism to hypomagnetic conditions, e.g., in outer space.

Such experiments are currently underway based on magnetic exposure systems developed at the Prokhorov General Physics Institute of the Russian Academy of Sciences, and operated in one of the Moscow clinical centers (Fig. 7). The 'Faraday' magnetic exposure system is used to record and reproduce natural magnetic storms and magnetic variations of the desired form. The 'Arfa' system, designed to study the effects of a magnetic vacuum, makes it possible to attenuate the external magnetic field by two orders of magnitude.

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