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Review Article

Influence of electromagnetic fields on the circadian rhythm: Implications for human health and disease

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ABSTRACT

Living organisms have evolved within the natural electromagnetic fields (EMFs) of the earth which comprise the global atmospheric electrical circuit, Schumann resonances (SRs) and the geomagnetic field. Research suggests that the circadian rhythm, which controls several physiological functions in the human body, can be influenced by light but also by the earth's EMFs. Cyclic solar disturbances, including sunspots and seasonal weakening of the geomagnetic field, can affect human health, possibly by disrupting the circadian rhythm and downstream physiological functions. Severe disruption of the circadian rhythm increases inflammation which can induce fatigue, fever and flu-like symptoms in a fraction of the population and worsen existing symptoms in old and diseased individuals, leading to periodic spikes of infectious and chronic diseases. Possible mechanisms underlying sensing of the earth's EMFs involve entrainment via electrons and electromagnetic waves, light-dependent radical pair formation in retina cryptochromes, and paramagnetic magnetite nanoparticles. Factors such as electromagnetic pollution from wireless devices, base antennas and low orbit internet satellites, shielding by non-conductive materials used in shoes and buildings, and local geomagnetic anomalies may also affect sensing of the earth's EMFs by the human body and contribute to circadian rhythm disruption and disease development.

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Introduction

Many ancestral traditions have promoted the view that the cosmos can influence life on earth. Taoists for instance consider that an invisible influence from the cosmos somehow affects some everyday occurrences. This subtle energy, often called *Qi*, is said to flow in and around the human body, and to vary with seasons and other cyclic solar and lunar processes. Taoists practice various activities such as *Qigong*, meditation, breathing exercises, acupuncture, and grounding in order to harmonize the body with this cosmic influence and promote health, vitality and longevity.

In the 1920s, Russian scientist Alexander Chizhevsky was among the first to observe that biological rhythms are entrained with the sun and earth [1]. Chizhevsky observed that high solar activity, as measured by the number of sunspots which reflect the sun's magnetic activity, was associated with social unrest, cardiovascular mortality, mental illnesses, and variations in crop production [1]. These periods of sunspot maxima occurred every 11 years according to the Schwabe cycle, which is due to periodic inversion of the sun's magnetic poles. Aleksandr Presman developed these ideas further and proposed that the EMFs of the earth provide biological information required for the growth, healing and optimal functioning of living organisms [2].

With the initial absence of a plausible mechanism and the difficulty in reproducing some early observations, these claims were initially dismissed and even today few people are aware of this field of research. However, a large body of evidence now indicates that biological organisms can sense small variations in the earth's EMFs and that solar disturbances can affect human health [3–7]. For instance, bacteria, honey bees, sea turtles, lobsters, monarch butterflies and migrating birds use the geomagnetic field as compass for direction [6], whereas humans may use the geomagnetic field as a Zeitgeber to entrain the circadian rhythm [3,5]. We review here the possible mechanisms underlying these effects and their potential impact on human health.

Effects of solar disturbances on human health

Following the work of Chizhevsky, various studies were performed to examine the effects of the sun on human health (reviewed recently in Ref. [7]). For instance, data from 6.3 million diagnoses made following a request for an ambulance in Moscow during three years of high solar activity (1979–1981) showed that 85,819 myocardial infarctions were linked in time with solar storms [8]. Over a period of 29 years, high solar activity in Minnesota was associated with reduced heart rate variability (HRV) and a 5% increase in cardiovascular mortality, compared with years of quiet solar activity [9]. Similarly, a large-scale case-crossover study involving data from Australia, France, New Zealand, Sweden and the United Kingdom concluded that solar storms were associated with a 19% increase in strokes [10].

Solar activity not only affects disease development, but also physiological functions in healthy individuals. For instance, astronauts in space showed a 30% reduction in HRV during a geomagnetic storm [11]. Hormones also show a cyclic variation that correlate with the sunspot cycle. Thus, in a man who collected urine for 15 years, it was possible to observe a statistically significant cyclic variation in the amount of 17-ketosteroids that matched the number of sunspots during that period [12]. Solar storms reduce melatonin levels by affecting enzymes required for its biosynthesis in the pineal gland and retina [13].

The British epidemiologist Robert Edgar Hope–Simpson expanded these findings when he observed that influenza pandemics were cyclic and coincided with periods of high sunspots [14]. It would later be shown that major human pandemics attributed to pathogenic bacteria, viruses or parasites occurred during periods of low or high sunspots [15] [Fig. 1]. Notably, the Covid-19 pandemic started during a sunspot minimum [Fig. 1], suggesting that electromagnetic factors may be involved. While some researchers proposed that sunspots and solar radiation may induce pandemics by increasing mutations that enhance microbial pathogenicity [15], the observation that sunspot minima and maxima are also associated with the development of several non-infectious diseases [7] indicates instead that the reason for the association may be due to disruption of host physiological functions during these periods, possibly via disturbances of the circadian rhythm and immune function which produce inflammation.

Yet, not everyone is sensitive to changes in solar activity, and it has been estimated that 10–15% of the population may react to solar and geomagnetic disturbances [4]. Physical factors such as latitude, humidity, temperature, and atmospheric pressure may also affect the level of magnetosensitivity in ways that are still poorly understood [16]. Some investigators also proposed that people indigenous to high latitudes are more sensitive to variations in EMFs and may have developed mechanisms to cope with enhanced geomagnetic disturbances occurring in Northern countries [4,17].

In a study performed in 2001–2003, 33 patients were separated according to either hypertension or a more severe cardiac disorder [16]. Most patients in the cardiac group were magnetosensitive (80%), whereas a smaller fraction (20%) of hypertensive subjects reacted to changes in the geomagnetic field. Magnetosensitivity increased in the more serious cardiac condition, which may reflect reduced resistance to stress in aging and diseased people. As noted by Zenchenko and Breus, four types of physiological responses to solar storms may occur, including variation within the normal physiological range (no signs), adaptation (compensation by the body to maintain homeostasis, possibly producing discomfort), failure to adaptation (thus producing symptoms), and possibly even death [7]. Aging and chronic diseases may reduce internal resistance and predispose individuals to disturbances in the earth's EMFs.

Two types of people who react to solar disturbances were described earlier based on HRV measurements and autonomic nervous responses, those who react by producing a parasympathetic response and those who react by increasing sympathetic tone [17]. As described above, a parasympathetic response may reflect a compensation to maintain homeostasis, whereas a sympathetic response may be due to a lower capacity to maintain equilibrium in response to stress. In this sense, perhaps solar and electromagnetic disturbances may

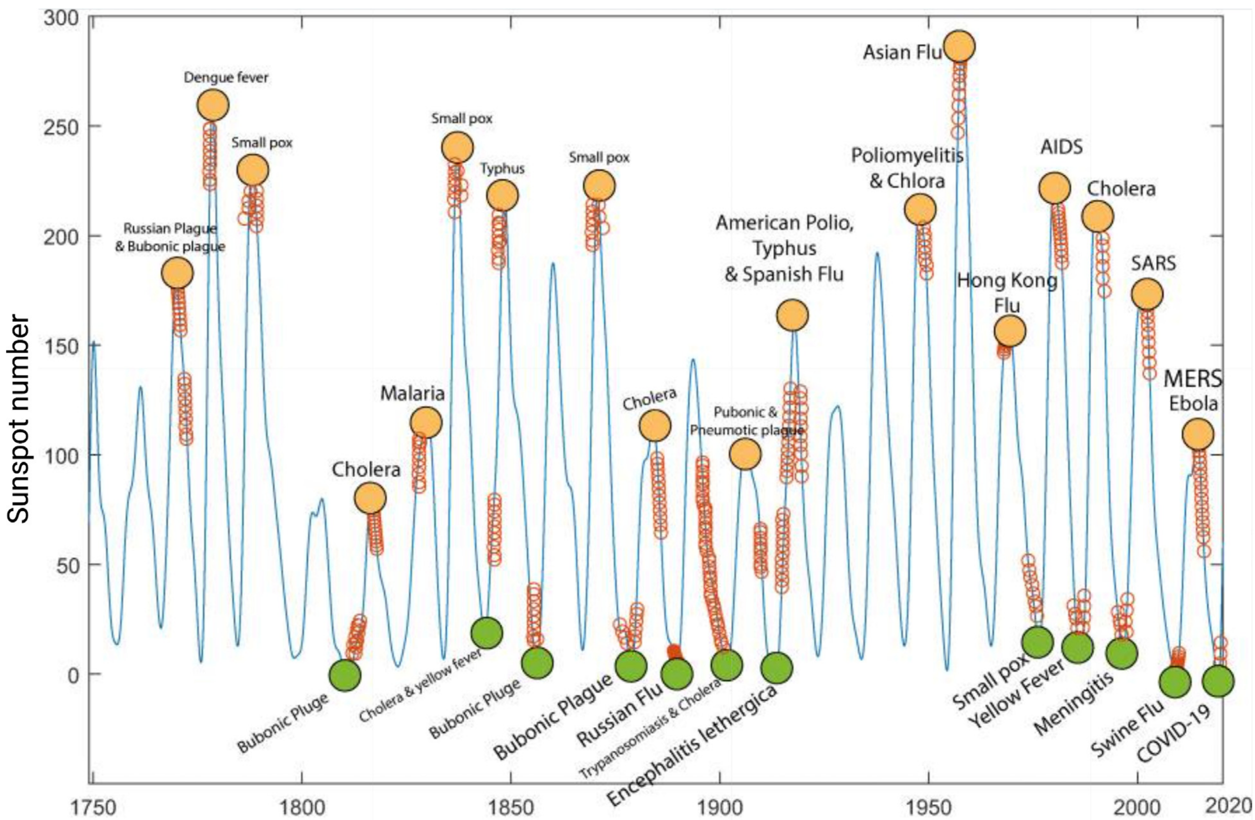

Fig. 1 Human pandemics occur during sunspot minima or maxima. Major human pandemics and epidemics attributed to bacteria, viruses and parasites have occurred during periods of high or low solar activity as measured by the monthly average number of sunspots. Orange circles correspond to pandemics or epidemics that occurred during sunspot maxima, whereas green circles represent pandemics or epidemics that occurred during sunspot minima. Note that the Covid-19 pandemic started in 2019 while sunspots were practically absent. The extreme severity of Covid-19 compared to past epidemics of SARS (2003) or swine flu (2009) suggests that, in addition to low sunspots, additional electromagnetic factors, including those from anthropogenic origins, may also be involved. Image reproduced from Nasirpour et al. [15], with permission from the publisher.

contribute to disease development mainly in susceptible and aging individuals.

Schumann resonances (SRs): the earth's electromagnetic gong

In 1952, Winfried Otto Schumann predicted that weak electromagnetic waves bounced between the ionosphere and the earth's surface [18]. The SRs were later detected and attributed to lightnings, which continually strike the globe 50–100 times per second [19], producing a fundamental frequency at 7.8 Hz, with additional peaks at around 15, 21, 30 and 45 Hz [4]. Electrical vibrations peaking at 8 Hz were later observed in various living organisms ranging from zooplankton, insects, snakes, sharks, and mammals [20]. Solar activity and lightnings also create the global atmospheric electrical circuit, a continual and substantial electrical current or movement of electrons between the ionosphere (positively charged, in general) and the earth (negatively charged).

Schumann's student, Herbert L. König, examined brain electroencephalograms (EEG) and noticed similarities between the fundamental SR of 7.8 Hz and alpha waves produced by the human brain in a relaxed but alert state, which also fall within the 7–14 Hz range [21]. Similarly, mental concentration is associated with brain waves of 14–30 Hz, which correspond with SR frequencies [22]. At first sight, brain waves may seem to be an epiphenomenon of neuronal activity and similarities between EEGs and SRs, mere coincidence. However, by producing artificial frequencies within the 3–5 Hz range, König was able to reduce mental performance and affect reaction time in volunteers, whereas 10 Hz improved these functions [23].

These intriguing observations were later repeated by several groups, including Klimesch and colleagues, who were able to improve cognitive performance in volunteers by applying transcranial magnetic stimulation in the alpha frequency [24]. In mice, repetitive transcranial magnetic stimulation at 15 Hz for 4 weeks reduced inflammation and signs of depression [25]. Elhalel et al. showed that applying a 90 nT magnetic field at a frequency of 7.8-Hz produces beneficial effects on rat cardiac myocytes, reducing H_2O_2-induced damage by around 40% [26]. These results suggested that humans may be continually or intermittently connected on a deep level with the earth's EMFs and that SRs may produce widespread health benefits.

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Careful analysis of SRs showed that their amplitude vary during the day. For instance, SR amplitude increases in the morning, reaching a peak between 8 and 10 AM, before returning to basal levels at night [27], suggesting a possible link between SRs and the circadian rhythm. Seminal experiments performed by Rütger Wever in Germany later showed that volunteers who were maintained for several weeks in an underground bunker that was shielded from the earth's EMFs with no outside light had a disrupted circadian period of 12–56 h instead of the usual 24 h [28,29]. The delay and desynchronization of the sleep-wake cycle could be reversed by placing an electric field generator at a frequency of 10 Hz in the room, suggesting that the SR may influence the circadian rhythm.

The circadian rhythm plays a critical role in synchronizing body functions according to the 24-h day–night cycle. In humans, the circadian rhythm controls sleep-wake behavior but also hormonal, metabolic, cardiovascular, neurological and immune functions [30]. Environmental cues including light, the earth's EMFs, temperature, and food intake represent the main Zeitgebers that entrain and influence the rhythmicity of the cycle. In the absence of environmental cues, the circadian rhythm continues to follow a free-running intrinsic period approximating 24 h, but phase disruption and amplitude issues eventually occur as the cycle is not reset and controlled properly. Disruption of the circadian rhythm affects the synchronization and amplitude of physiological functions and can occur following any activity that is not in synch with the cycle, including sleep deprivation, jet lag, nightshift work and eating at night [31,32]. This affects a wide range of cellular functions (e.g., metabolism, immunity, cell proliferation) and contributes to inflammation and chronic diseases such as type 2 diabetes, obesity, infection, cardiovascular disease, and cancer [31,32]. By inducing inflammation and impairing immune functions, a disrupted circadian rhythm increases mortality in response to respiratory tract infections such as influenza and Covid-19 [33,34].

In the seventeenth century, the Dutch mathematician Christiaan Huygens observed that when two pendulum clocks are hung on the same walls for some time, they spontaneously start to synchronize their oscillation frequency albeit in opposite directions to each other. Similarly, synchronization of biological rhythms with environmental EMFs may represent a mechanism that occurs spontaneously between two electromagnetic entities, thereby allowing living organisms to save energy and maintain internal coherence by coupling biological functions with periodic environmental signals. Some authors have proposed that biological organisms may have become phase-locked with the EMFs of the environment over years of evolution [20]. Recent research indicates that oscillations in brain activity are coupled to several organs in the body, including the nervous system and gastrointestinal tract, implying that this form of entrainment may regulate organ functions [35]. Entrainment of body functions with the earth's EMFs may occur via natural electromagnetic waves such as SRs or with electrons from the global atmospheric electrical circuit.

A potential mechanism to explain the effects of solar storms described above is that they may affect the SRs and therefore interfere with the resonance between the earth and the human brain [36]. Consistent with this hypothesis, studies indicate that solar storms induce changes in the fundamental SR frequency, with X-ray bursts increasing the frequency, while solar proton events decrease it [37]. Major solar storms thus mainly affect SR frequencies, without affecting the amplitude of the signal [38].

Variations in the SRs correlate with changes in brain waves. For instance, Pobachenko et al. observed real-time coherence between variations in the SRs and brain activity within the 6–16 Hz range [39]. Similarly, Rollin McCraty and colleagues observed that HRV correlates in real time with the power of the SRs [40]. Another study showed that an increase in natural SR power is associated with higher HRV and parasympathetic activity in humans [41]. It thus appears that SRs provide health benefits, at least in part by entraining or influencing the circadian rhythm.

The earth's geomagnetic field as a Zeitgeber

Frank A. Brown observed in the 1960s that various organisms including quails, snails, crabs, and mice rely heavily on the geomagnetic field for orientation in space and time [42]. In 1978, Aleksandr P. Dubrov compiled a large body of observations indicating that variations in the geomagnetic field coincided with changes in cellular activity in a wide range of organisms [3]. For instance, cellular respiration in plants, worms and rodents all varied in a synchronous manner with the diurnal variation of the intensity of the geomagnetic field [3]. Experiments performed in shielded environments showed that living organisms need the geomagnetic field to function properly as it is required for the regulation of various cellular processes, including chromatin condensation, DNA replication, gene expression, cell cycle, enzyme and mitochondria function, and cell migration and differentiation, among others (reviewed recently in Ref. [6]). In the absence of the geomagnetic field, mice eventually lose their fitness [43] and become sterile [44] and anxious [45]; while humans show disrupted circadian rhythms, reduced metabolism, gastrointestinal disorders, and altered immune cell numbers [46].

While the magnetic field is often described as static, it is actually modulated by the sun and varies in intensity in a diurnal manner [5,47,48]. Notably, diurnal variation in the intensity of the geomagnetic field closely follows that of the SRs described above, peaking at around 8–10 AM in the morning, and returning to basal level around 6 PM in the evening [48] [Fig. 2A]. An apparent correlation can be seen between the daily variation in the geomagnetic field and the morning peak of circadian genes (e.g., *PER3*) and hormones like cortisol that are characteristic of the circadian rhythm [Fig. 2B and C]. Accordingly, several authors have proposed that the geomagnetic field may act as a Zeitgeber [3,5,13] similarly to light and temperature.

Surprisingly, the heart's magnetic field can be intermittently synchronized with the geomagnetic field, as both can oscillate at 0.1 Hz [49]. People's HRV also correlates in real time with variations in the geomagnetic field [40]. In insects, simulated geomagnetic storms can disturb the circadian rhythm [50]. Solar storms also affect the circadian rhythm in humans, reducing the production of melatonin and increasing levels of the stress hormone cortisol, effects that are more

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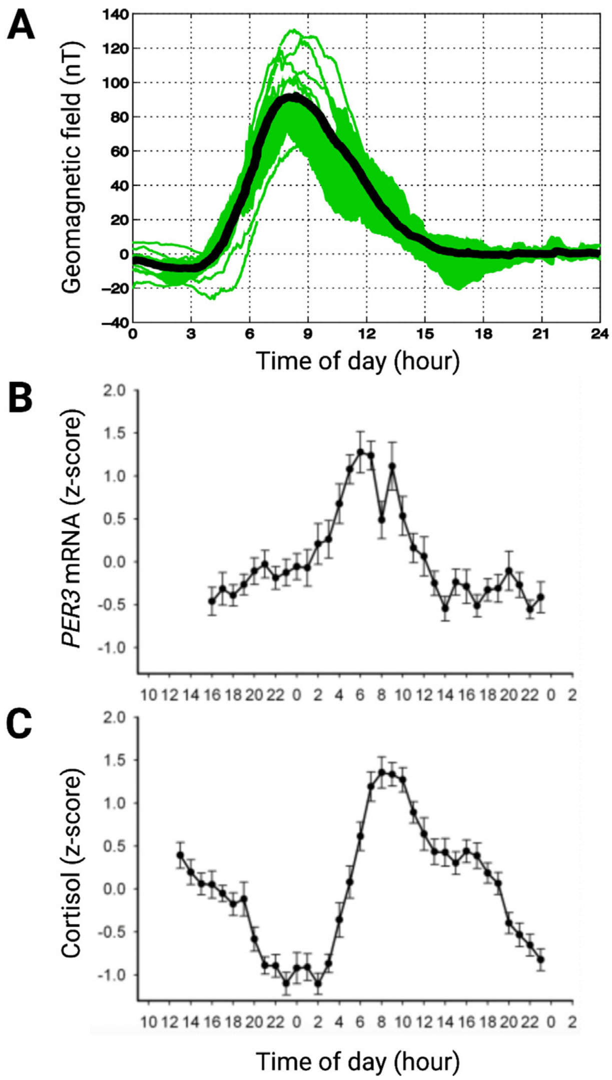

Fig. 2 Diurnal variations in the geomagnetic field coincide with the human circadian rhythm. (A) Quiet daily variations of the geomagnetic field. Green curves represent geomagnetic daily variations for individual days, while the black curve represents the average value. Measurements were made in Addis Ababa in November 2012. (B) Diurnal variation in the mRNA expression of the circadian marker PER3. Data are plotted relative to clock time and expression represents relative copy number against glyceraldehyde-3 phosphate dehydrogenase (GAPDH). (C) Diurnal variation in blood cortisol level. Measurements of the geomagnetic field at the time and location where the PER3 and cortisol experiments were performed may produce an even better correlation, but were not available here. Image in A is reproduced from Joseph et al. [48], with permission from the publisher. Images B and C are reproduced from Archer et al. [100], with permission from the publisher.

pronounced in patients with coronary heart disease compared to healthy controls [51]. Conversely, enhancing the circadian rhythm can be used to reduce cancer burden in mice [52]. Re-entraining the circadian rhythm thus appears to be an important concept to prevent and treat chronic diseases.

The geomagnetic field averages 35 μT near equatorial regions and 70 μT around the earth's magnetic poles. Solar storms can induce variations of 5 μT at high latitudes and 1 μT near the equator. For this reason, solar and geomagnetic disturbances produce larger effects at high latitudes [4]. Large interindividual variability in the period, phase and amplitude of physiological functions entrained by the circadian rhythm has been observed in living organisms such as zebrafish [53], which may reflect variations in magnetosensitivity.

One of the possible mechanisms linking the geomagnetic field and entrainment of the circadian rhythm involves proteins called cryptochromes in the retina [54]. In migrating birds, light induces the formation of free radical pairs in retinal cryptochromes and these radical pairs are thought to be sensitive to variations of the geomagnetic field and may act as a compass [55]. Within the context of the circadian rhythm, the radical pair formed in the flavin adenine dinucleotide (FAD) of cryptochromes may act as an on/off switch that can induce an electron current to nearby tryptophan and tyrosine residues and regulate downstream signaling to clock proteins [56]. Cryptochromes are also sensitive to the slow diurnal variation of the geomagnetic field and can lead to degradation of circadian rhythm proteins to reset a new circadian cycle and regulate ~40% of the genome [57]. Recent studies suggest that a similar mechanism involving radical pairs and cryptochromes may control the circadian rhythm in various organisms [58,59].

Another possible mechanism involves magnetite nanoparticles which have been detected in the human brain, especially in the cerebellum and brainstem [60]. Paramagnetic minerals have long been associated with increased plant growth and health benefits in humans, possibly due to their ability to amplify the geomagnetic field [61]. Thus, magnetite nanoparticles may influence specific organs, nerves and glands based on the time-varying geomagnetic field. Intracellular water may react to the enhanced magnetic field by forming exclusion zone (EZ) water [62]—a gel-like phase with a net negative charge that forms on hydrophilic surfaces such as proteins and cell membranes [63]—leading to cellular activation based on phase transition with bulk water [64]. Besides, another possible mechanism involves atmospheric electrons from the global electrical circuit which can migrate along geomagnetic field lines and influence body functions according to time of the day.

Seasonality of infectious and chronic diseases

Human cells show daily variation in their activities, including variations in cortisol levels, blood cell count, functioning of peripheral organs, lymphocyte proliferation and cytokine levels [65]. Disruption of the circadian rhythm may also affect immune functions and induce inflammation. For instance, night shift workers show a higher incidence of common colds with more severe symptoms [66]. Chronic disruption of the circadian rhythm in healthy individuals, especially in aging individuals, may also contribute to reducing resistance to viral infection. Disruption of the circadian rhythm is also a main feature of severe Covid-19 cases [34].

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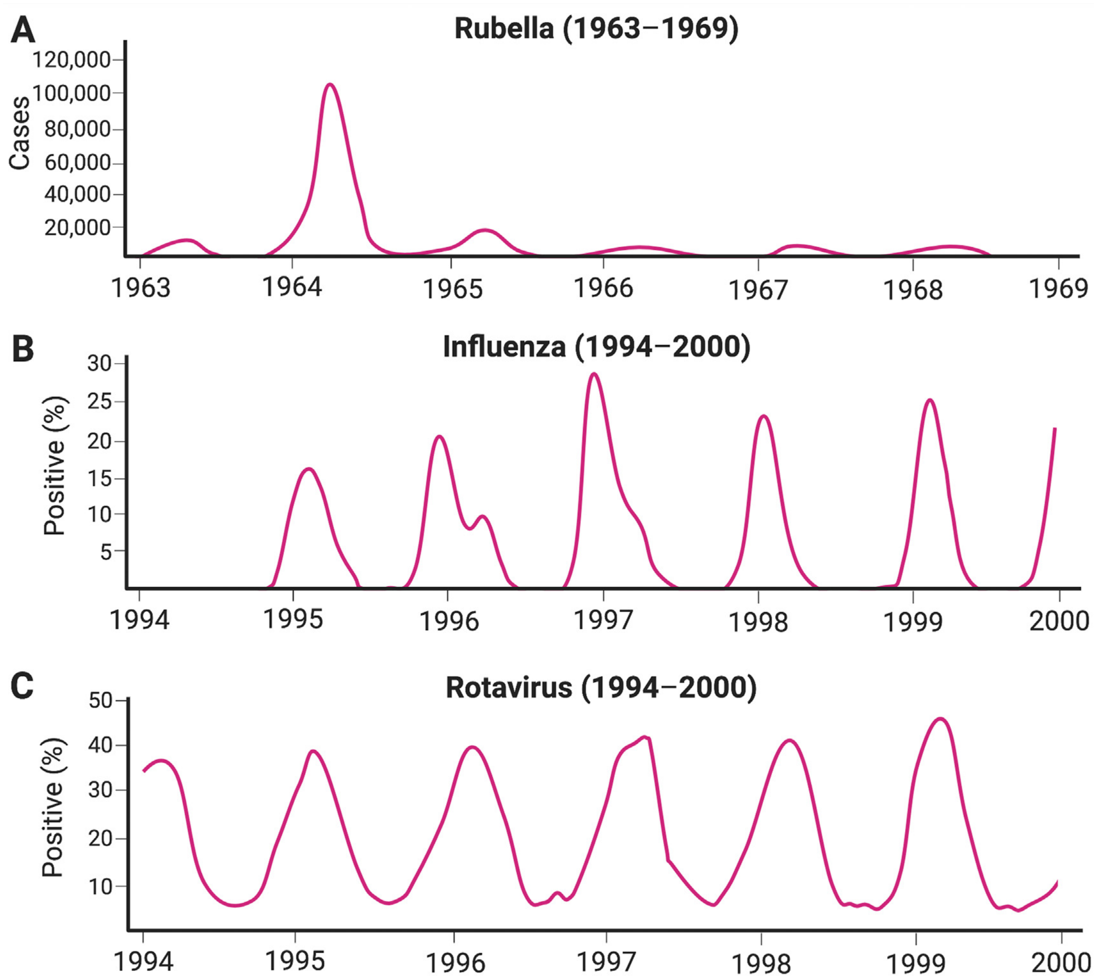

Fig. 3 Seasonality of infectious diseases in the United States. (A) Reported cases of rubella and percentage of positive cases of (B) influenza and (C) rotavirus infection for the time indicated. Note that the peaks occur during the winter months. Image reproduced from the work of Dowell [67], which is in the public domain.

In Northern countries such as the U.S., Canada and Europe, infectious diseases such as rubella, influenza and rotavirus infections are seasonal and recur every year during the winter [67] [Fig. 3A–C]. In fact, most chronic diseases increase during this period, including heart disease, cancer, stroke, type 2 diabetes, pneumonia and kidney disease [68]. It has been hypothesized that low solar activity could lead to vitamin D deficiency in the winter which in turn may affect immune function. Given that sunlight can decrease the infectivity of some pathogens, low solar intensity in the winter may also produce a higher burden of pathogens. Hope–Simpson had observed the seasonal variation in influenza epidemics around the globe and had attributed this to variation of the sun but not to weather [69]. However, the underlying reason for this seasonality remained unclear.

Within the Northern hemisphere, SRs and the geomagnetic field also vary throughout the year, showing reduced amplitude in winter months [27,70] [Fig. 4A]. This drop in the intensity of the SRs and geomagnetic field coincides with variations in the expression of ~23% of protein-coding genes in the genome [Fig. 4B and C], including in genes related to the circadian rhythm [71]. The pattern of expression is inverted in the Southern hemisphere [Fig. 4D]. Notably, immune cells spontaneously produce a pro-inflammatory profile during the winter in Northern countries [71] [Fig. 4E and F], which may contribute to the development of influenza and flu-like symptoms such as fever, fatigue, headaches, cough and congestion in a fraction of the population, as well as worsening of chronic disease conditions. Accordingly, influenza epidemics occur in the winter in countries of the Southern hemisphere such as Australia and New Zealand, consistent with the inverted pattern of gene expression compared to Northern countries [Fig. 4D]. For chronic diseases, the strongest seasonal periodicity is observed for heart disease, stroke, respiratory disease and kidney disease [68], suggesting that the heart, brain, lungs and kidneys are particularly sensitive to EMFs.

A large number of biological phenomena observed over the course of a year such as white blood cell count, plant respiration, the ability of algae to reduce nitrate, the metabolic rate of beans, and the growth of grass were also shown to be synchronous with annual variation in the intensity of the geomagnetic field [3]. It thus appears that the global electrical circuit, SRs and geomagnetic field not only regulate and

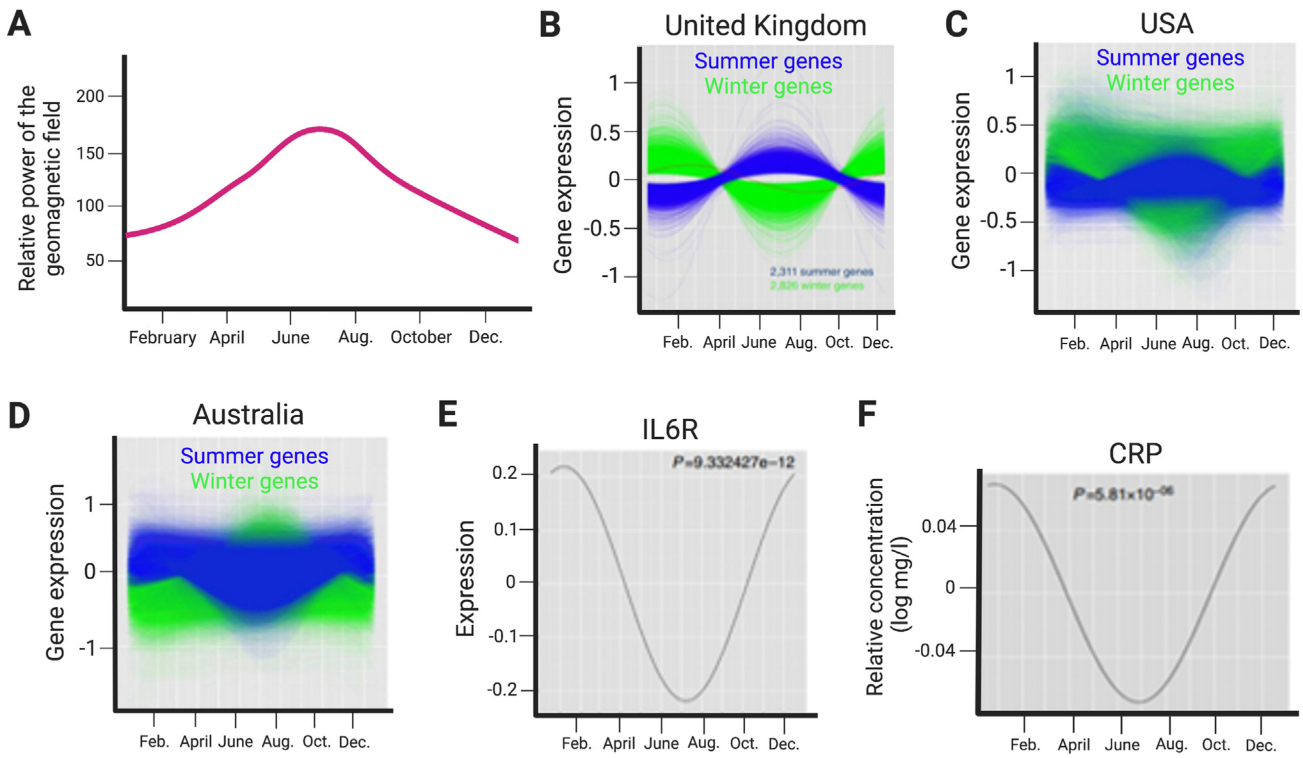

Fig. 4 Annual variations in the geomagnetic field coincide with variations in gene expression in human cells. (A) Relative power of the geomagnetic field. Measurements were done in 2014 in Lithuania. (B) Expression of 5136 genes (23% of the protein-coding genome) in human peripheral blood mononuclear cells (PBMCs) shows seasonality in the BABYDIET dataset (genome-wide significance, $P < 1.52 \times 10^{-6}$). (C) Gene expression in PBMCs from asthmatic subjects in the United States. (D) Gene expression in PBMCs from asthmatic subjects in Australia. (E) Expression of interleukin-6 receptor (IL6R) in European people. (F) Circulating C-reactive protein (CRP) in European people. Image A is reproduced from the work of Jaruševičius et al. [70], which is under a Creative Commons CC BY license. Images B–F are reproduced from Dopico et al. [71], which is under a Creative Commons CC BY license.

influence the circadian rhythm in various organisms but may also be involved in the seasonality of human diseases.

Effects of electromagnetic pollution

In addition to the natural EMFs of the earth, the human body and the circadian rhythm can also be affected by anthropogenic sources of electromagnetic pollution. Technological revolutions related to the use of electricity, internet, and wireless telecommunications have considerably increased our exposure to non-ionizing electromagnetic radiation. For instance, levels of radiofrequency electromagnetic radiation around the 1 GHz band used mainly for wireless devices has increased by around 10^{18} times compared to natural baseline levels [72]. Modern electrical and wireless devices such as light-emitting diodes (LEDs), smart phones, Wi-Fi, and laptop computers are widely seen as must-have conveniences nowadays. However, a growing number of scientists and citizens have raised concerns about the health risks associated with their indiscriminate use [72–75]. Although this research is still controversial, long-term use of cell phones and wireless devices has been implicated in the development of attention deficit and hyperactivity disorder, cognitive impairment, infertility, neurodegenerative disorders, immune system problems, cardiovascular disease, and cancer [72–74].

Safety standards for cell phones are based only on thermal effects in the short term (6 or 30 min of exposure), while the long-term safety of cell phone towers and antennas has not been fully investigated. However, it is now clear that living organisms react to weak variations of EMFs such as the action described above for cryptochromes which may influence the circadian rhythm [5,56]. Furthermore, important aspects of real-time exposure to radiofrequencies have been overlooked, including permanent exposure to multiple sources, signal polarization, the sensitivity of specific organs or age groups, combined exposure with other environmental toxins, and interference with the natural EMFs of the earth. Countless studies have shown that low-intensity wireless radiofrequencies such as those produced by cell phones and antennas can produce biological effects without affecting body temperature [75,76]. For instance, wireless electromagnetic waves can induce DNA damage and oxidation, inhibit mitochondria and energy production, activate voltage-dependent calcium channels, induce cellular stress and heat-shock proteins, alter immune functions and affect the blood–brain barrier [75,76]. Notably, the effects of wireless electromagnetic radiation have been shown to be attenuated by voltage-dependent calcium channel inhibitors in laboratory animals,

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indicating that these proteins are involved in the non-thermal effects produced by wireless electromagnetic waves [77]. Yet, other studies have reported no detrimental effects on some of these markers, possibly due to differences in methodologies and other factors, which further delays acceptance of detrimental effects of wireless EMFs.

The advent of the internet of things (IoT) and the 5G wireless network is seen by many experts as a major threat to human health [75]. 5G relies on radiofrequencies used for previous networks (MHz range) but also higher microwave frequencies (1–100 GHz) that fall into the millimeter range (30–300 GHz). Given that these microwaves of higher frequencies are partially blocked by building walls, rain and vegetation, it was planned to increase the number of antennas and their power intensity, which can considerably increase the levels of exposition. These levels of exposition are further multiplied by the number of telecommunication companies in each region (usually from 2 to 6), which install antennas at the same locations (in addition to the existing 3G and 4G towers).

While no safety studies have been conducted yet to assess the health effects of the 5G network, which remains to be fully implemented, preliminary studies show that living in close proximity to 5G antennas can lead to microwave sickness [78], a condition identified in radar operators chronically exposed to high levels of microwaves and characterized by flu-like symptoms such as headaches, fever, fatigue, diarrhea, vomiting, tinnitus, dizziness, body aches, poor concentration, cardiovascular abnormalities, insomnia and anxiety [79]. Widespread protests by the public and health experts have occurred in various cities throughout the world and several international appeals have requested a moratorium on 5G safety. However, these red flags and safety concerns have been ignored and most countries have rushed ahead with the rollout of this novel wireless technology, including tens of thousands of low orbit satellites already approved to provide high-speed internet to every corner of the earth. The possibility that this new source of electromagnetic pollution may affect the human circadian rhythm and induce inflammation in old and diseased individuals remains to be examined.

Epidemiological studies and anecdotal observations indicate that people living near cell phone towers and antennas show a higher incidence of headaches, tinnitus, dizziness, concentration problems, fatigue, anxiety, insomnia, depression and increased rates of suicides, neurodegenerative diseases and cancer [80]. Based on epidemiological studies and meta-analyses of electric and magnetic fields and long-term use of cell phones, the International Agency for Research on Cancer (IARC) classified wireless radiofrequencies as possibly carcinogenic to humans [81]. The safety guidelines based on thermal effects are clearly inadequate.

The lack of acceptance of the detrimental effects of wireless EMFs in public opinion may be due to the fact that EMFs do not appear to produce obvious symptoms in the large majority of young and healthy individuals in the short term. However, the situation may be different for old individuals and people with chronic diseases who show reduced resistance to various forms of stress. Reduced stress resistance in older individuals and people with chronic diseases has been attributed to various factors including reduced amplitude or phase shift of the circadian rhythm [12]. The disrupted circadian rhythm may lead to a pro-inflammatory immune cell profile, a condition also called inflammaging, which can contribute to disease progression.

Within the context of the Covid-19 pandemic, some symptoms of long-Covid-19, which affects 50% of cases in the U.S., are highly similar to microwave sickness [79]. While both conditions present symptoms that are common and nonspecific such as fever, fatigue, headaches, congestion and cough, other symptoms may be more characteristic of microwave toxicity, including tinnitus, loss of smell, pain in the back of the skull (brainstem), dizziness, nausea, heart palpitations, difficulty to focus, cognitive dysfunction, anxiety, and insomnia. While all these symptoms have been attributed to SARS-CoV-2 infection, the possibility exists that at least some of these symptoms may be caused by microwave toxicity. For instance, Allan H. Frey observed that some radar operators can hear microwaves as ringing and clicking sounds [82], a phenomenon known today as the "Frey effect." Radiofrequency waves from cell phones can also produce anxiety by reducing the number of pyramidal neurons in the hippocampus in rodents [83]. In some people, radiofrequency exposure can induce dizziness and nausea [84], as well as cardiac changes such as arrhythmia, with possible involvement in cardiovascular disease [85].

It has been reported that radiofrequencies within the MHz range—similar to those emitted by cell phones and wireless telecommunication antennas—can disrupt magnetoreception in migratory birds [86–88]. The circadian rhythm of insects, rats and mammals can be disrupted by radiofrequencies used for cell phones and antennas [89]. The possibility exists that wireless antennas and low orbit satellites may affect the circadian rhythm and human health by affecting the global electrical circuit, the local geomagnetic field or the sensing of the earth's EMFs by the human body.

Interestingly, anthropogenic EMFs can inhibit mitochondrial metabolism and ATP production. For instance, experiments in bees exposed to cell phone radiation for 10 min led to an increase of cholesterol, triglycerides, and glucose into the lymph [90], possibly due to inhibition of mitochondria and release of these nutrients back into the circulatory system. Electromagnetic radiation from cell phones, laptops and electrical devices may inhibit mitochondria by producing reactive oxygen species and inducing electron leakage from the electron transport chain [91]. These observations might have implications for the development of type 2 diabetes, cardiovascular disease, neurodegenerative diseases and premature aging, which are all associated with mitochondrial defects [75,92]. Investigators such as Leif G. Salford—who made the observation that low-intensity radiofrequencies can breach the blood–brain barrier in rodents—suggested that anthropogenic microwaves may produce biological effects by interfering with endogenous electromagnetic signals [22], which were first described by investigators such as Herbert Fröhlich and later found to induce protein conformation changes in a non-thermal manner [93].

Various mechanisms have been proposed to explain the detrimental effects of man-made EMFs observed on human health. Yet, thousands of studies showing non-thermal effects of low-intensity microwaves continue to be ignored [72–75,80]. Until more people recognize the adverse impact of

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man-made EMFs on human health and nature in general, the potential benefits of designing technologies and environments that are more electromagnetically bio-friendly deserve more attention.

Reconnecting with the earth and nature

Grounding or "earthing" refers to making direct contact with the earth while standing barefoot or lying down on the ground. Shoes and floors made of synthetic, non-conductive materials may block the SRs or electrons from the global electrical circuit. Similarly, some materials used to build modern houses and buildings can attenuate or distort the geomagnetic field, especially if metals are used as in the case of reinforced concrete structures. Higher SR amplitude is detected in rural areas compared to industrial areas [94], suggesting some forms of interference due to shielding or anthropogenic EMFs. The urban lifestyle is therefore likely to be associated with a weakening or masking of the natural EMFs.

The main rationale behind grounding is that the human body has evolved while being in direct contact with the earth. We have seen that the earth's EMF provides health benefits for humans, as long as it is not disturbed by solar storms, sunspots or seasonal variations in the geomagnetic field. Preliminary clinical studies have shown that grounding produces a wide range of health benefits, including reducing inflammation, pain, fatigue, blood pressure and symptoms of autoimmune diseases [95].

James L. Oschman proposed that grounding may help entrain the circadian rhythm [96], and several observations support this hypothesis. For instance, grounding has been shown to increase brain alpha waves [97], which are not only observed in the relaxed mental state but also show similarities with the fundamental SR as described above. Grounding improves sleep and normalizes the secretion of cortisol and melatonin [98]. People who sleep grounded reported better quality of sleep and showed reduced levels of night-time cortisol [98]. Levels of cortisol monitored during the day were also more synchronized with the circadian rhythm. Anecdotal evidence suggests that grounding may reduce the effects of jet lag, possibly by reinforcing the effects of SRs. If grounding provides benefits via the earth's EMFs and electrons from the global electrical circuit, it is likely that sunspots, solar storms, seasonal weakening of the geomagnetic field, and local geomagnetic anomalies may at times interfere with these effects.

Conclusion and future perspectives

Many observations described here suggest that the time-varying atmospheric and earth electrons, SRs and geomagnetic field may provide environmental cues that entrain the circadian rhythm and influence a wide range of physiological functions. Cyclic and spontaneous variations in solar activity and the geomagnetic field can disrupt the human circadian rhythm and contribute to the development of infectious and chronic diseases. However, only a fraction of the population usually reacts to changes in solar and geomagnetic activity; their susceptibility may be due to aging, existing chronic diseases, or reduced resistance to stress. The current health status of the individual and genetic background may play a critical role in the response to electromagnetic perturbations. In this case, remaining healthy through proper nutrition, regular exercise, appropriate sunlight exposure, intermittent fasting, intake of phytochemicals, trace minerals and vitamins, and avoidance of toxins may help to prevent the development of symptoms and chronic diseases in spite of changes in the electromagnetic context of the earth. The adoption of appropriate electromagnetic hygiene measures at home, the office and during daily activities may also help individuals to maintain or regain health. In addition, major changes in anthropogenic EMFs represent an environmental stress that can affect human health in various ways.

Major human pandemics occur during periods of sunspot minima and maxima [15], suggesting that electromagnetic factors may have played a role in the Covid-19 pandemic. Other electromagnetic factors may also have been involved, including seasonal weakening of the geomagnetic field and environmental factors such as local geomagnetic anomalies and low orbit internet satellites, an area that requires further research. It remains unclear how the recent increase in electromagnetic pollution from wireless devices, cell phone antennas and low orbit satellites may have influenced immune systems and human health in general. These electromagnetic factors require further attention as a large increase of excess mortality (i.e., more than four times higher than Covid-19 mortality) has been observed worldwide since the start of the pandemic [99].

In retrospect, it appears that ancient spiritual traditions were correct in believing that there is a connection between the sun, the earth and the human body. As the human body is sensitive to natural and anthropogenic EMFs, recent advances in the field of bioelectromagnetism, circadian rhythms, and grounding, as well as a better understanding of the interference by man-made electromagnetic pollution may help to maintain optimal health and reduce the development of chronic disease.

Disclaimer Statement

J.D.Y. is Chairman of the Board of Chang Gung Biotechnology. J.M., D.M.O., and J.D.Y. are named on patents held jointly by Chang Gung University and Chang Gung Biotechnology related to the preparation and use of dietary supplements. G.C. is Director and Chairman of the Board of the Earthing Institute.

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