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ASTROBIOLOGY

How the Geomagnetic Field Influences Life on Earth – An Integrated Approach to Geomagnetobiology

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Abstract
Earth is one of the inner planets of the Solar System, but – unlike the others – it has an oxidising atmosphere, relatively stable temperature, and a constant geomagnetic field (GMF). The GMF does not only protect life on Earth against the solar wind and cosmic rays, but it also shields the atmosphere itself, thus creating relatively stable environmental conditions. What is more, the GMF could have influenced the origins of life: organisms from archaea to plants and animals may have been using the GMF as a source of spatial information since the very beginning. Although the GMF is constant, it does undergo various changes, some of which, e.g. a reversal of the poles, weaken the field significantly or even lead to its short-term disappearance. This may result in considerable climatic changes and an increased frequency of mutations caused by the solar wind and cosmic radiation. This review analyses data on the influence of the GMF on different aspects of life and it also presents current knowledge in the area. In conclusion, the GMF has a positive impact on living organisms, whereas a diminishing or disappearing GMF negatively affects living organisms. The influence of the GMF may also be an important factor determining both survival of terrestrial organisms outside Earth and the emergence of life on other planets.

Keywords Geomagnetobiology · Evolution · Astrobiology

Introduction

Earth is one of the inner planets of the Solar System and like its two closest neighbours, Venus and Mars, it is a rocky planet (Rao 1980). However, unlike Mars and Venus, Earth is habitable, has an oxidising atmosphere with a well-developed ozone layer, and – above all – a unique magnetic field.

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Earth's magnetic field, also called the geomagnetic field (GMF), is a global vector field, which means that in each point of space the magnetic field is defined by a vector of the magnetic field. This vector is represented by coordinates in the Geographic Coordinate System (GCS). In the International System of Units (SI) the intensity of the GMF is measured in tesla units (T), although gauss units (G) are still frequently used. Its strength varies naturally, ranging from approximately 25 to 65 μT (0.25–0.65 G) (Finlay et al. 2010).

Although the GMF can be considered as a sum of several different fields, such as a uniform magnetic field, continental magnetic field, anomalous magnetic field, external magnetic field, and a variation field, the main role is played by a uniform magnetic field (Dubrov 1978). The GMF could be also considered as a sum of two components, such as the Internal or the Main Field (generated by geodynamo) (Bullard 1949) and the External Field (generated by interactions between the solar wind and the Earth's ionosphere) (Glassmeier and Vogt 2010). Currently, Earth's magnetic poles are near geographical poles (Clark 1979), however, a long-term drift of geomagnetic poles (World Data Center for Geomagnetism 2012) can be observed. Still, the GMF is considered as a constant magnetic field, which means that it is free from variations with a period of a year or shorter, because its main components, i.e. uniform magnetic field, continental magnetic field, anomalous magnetic field, (Dubrov 1978) are constant. Rapid changes of less than a year (Dubrov 1978) in the GMF occur only in the time-varying component of the GMF of a very low intensity, known as the 'variation field', which is generated by electric current systems in the ionosphere (Dubrov 1978).

According to a dominant hypothesis, Earth did not have a magnetic field in its early days. Originally, weak magnetic fields in our galaxy induced fluid movement in the core of Earth, leading to a relatively quick formation of the field (Clark 1979). Undoubtedly, the Earth's GMF had already existed when life appeared on the planet 3.5–4.3 billion years ago (Tarduno et al. 2010; Gargaud et al. 2012).

Scientists have long been interested in the origins and evolution of life on Earth, and the role the GMF played in the process (Kirschvink et al. 1985). The knowledge of this relationship is very important not only for the understanding of the origins of life on Earth and its further evolution, but also for chances of finding life on other planets and/or moons.

Having searched the phrase 'Geomagnetic field' in scientific browsers, i.e. the SCOPUS and the Web of Science (WoS) (Fig. 1a; SI 1), we found over 21,000 and 19,000 hits, respectively. The oldest paper dates back to the first half of the twentieth century (McNish 1940), a period when the dynamo theory was formulated (McNish 1940). Since then, the interest in this field has been constantly rising. As a result, a growing number of studies and papers have appeared that focus on the GMF as a fundamental environmental drive in the evolution life on Earth.

Apart from the original term 'geomagnetic field', 'geomagnetism' has also been used since 1939 (Fleming 1939). For example, in the SCOPUS the number of hits amounted to over 600 until the end of 1970s, while in the WoS it was a tenth of that number (Fig. 1b; SI 1). Besides, until the end of 2020 there was a large discrepancy between results in these databases with nearly 18,000 hits in the SCOPUS and only a little over 1,000 in the WoS (Fig. 1b; SI 1). Nevertheless, the issue has become increasingly studied over the years.

At first, scientists were mostly interested in the impact of the GMF on animals. The phrases 'Geomagnetic Field' and 'Animals' appeared alongside in papers before 1970 (SCOPUS) or the early 1970s (WoS) (SI 1). Soon, scientists took interest in plants, and first studies on the impact of Earth's magnetic field on plants appeared in the SCOPUS between 1970 and 1980, and a decade later in 1990, according to the WoS (SI 1). At the same time, the term 'Magnetoreception' was coined, and 15 hits can be spotted before

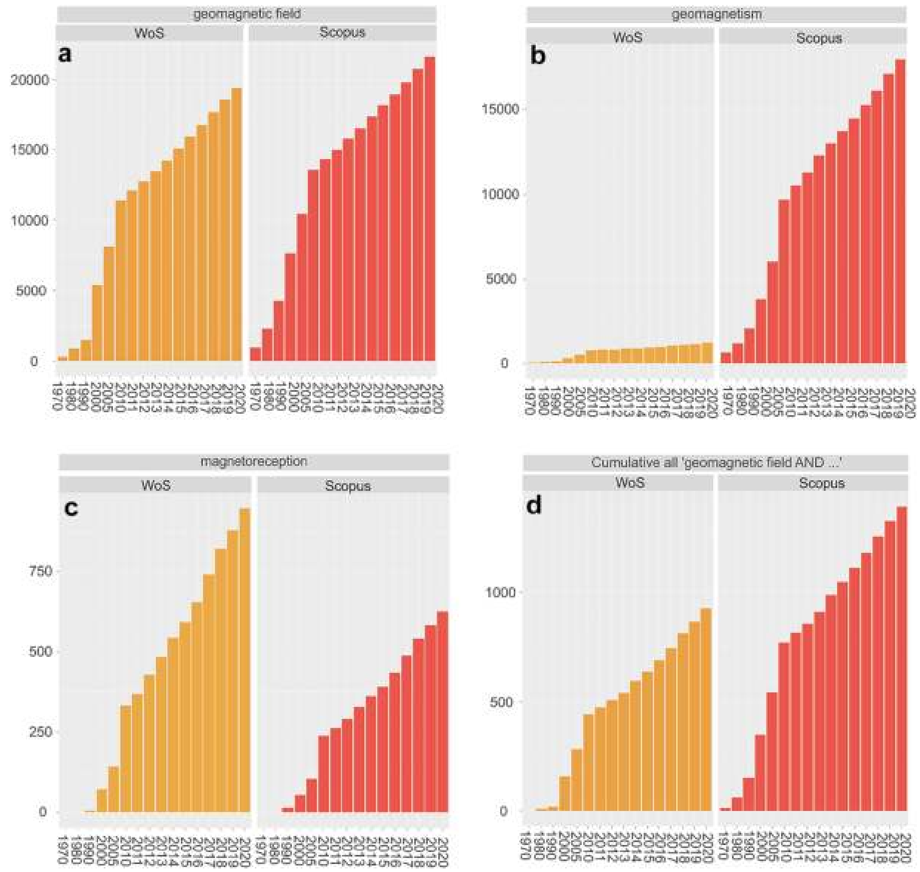

Fig. 1 Changes in interest in GMF-related topics expressed as changes in the number of publications, in subsequent time periods (Scopus/WoS) until the end of 2020 (data obtained 06.05.2021) for keywords and phrases, **a** 'Geomagnetic Field', **b** 'Geomagnetism', **c** 'Magnetoreception' and **d** Cumulative results for all phrases 'Geomagnetic Field AND

1990 (SCOPUS), and seven between 1980–1990 (WoS) (Fig. 1c; SI 1). Apart from studies on the GMF's impact on animals, cells were also taken into account with the first paper before 1970, six others that included 'Geomagnetic field' and 'cells' (SCOPUS) or six further papers in the following decade (WoS) (SI 1).

Subsequently, further questions were raised, for example how the geomagnetic reversal contributed to mass extinctions. In fact, this issue has been rarely discussed: the first paper appeared before 1980 (SCOPUS) or in the early 1990s (WoS) (SI 1). At present, only 27 papers are recorded in the WoS and 26 in the SCOPUS (SI 1). Finally, the term 'magnetofossils' occasionally appears in both databases in the context of the geomagnetic field, it is one hit in SCOPUS and two in WoS until the end of 2020 (SI 1).

Our analyses show that the GMF and its impact on life on Earth raised interest in the late 1930s, and since then it has been increasing (SI 1). This is visible in results from both SCOPUS and WoS for all the phrases 'Geomagnetic Field' (Fig. 1a), 'Geomagnetism' (Fig. 1b), 'Magnetoreception' (Fig. 1c). and for cumulative results for phrases 'Geomagnetic Field AND …' (Fig. 1d). Nevertheless, there is no comprehensive review of the knowledge on the topic. Many researchers focus on a small fraction of this broad research field, testing only the direct or indirect effects of the GMF. So far, the broadest review in the field of geomagnetobiology has been Dubrov's work 'The geomagnetic field and life: Geomagnetobiology', However, it was published in 1978, which makes it outdated in many aspects. Similarly, 'Magnetite Biomineralisation and Magnetoreception in Organisms: A New Biomagnetism' published in 1985 (Kirschvink et al. 1985) provides an in-depth overview of the state of the knowledge in magnetosome-based magnetoreception and the magnetite biomineralisation process itself, Still, it is also an old book and there is a shortage of discoveries from last thirty-five years. Another problem concerns review articles from that time, such as 'Bird orientation and the geomagnetic field: A review.' (Ossenkopp and Barbeito 1978), 'Biophysics of geomagnetic field detection' (Kalmijn 1981) or 'How the geomagnetic field vector reverses polarity' (Prévot et al. 1985). First of all, they are outdated in some respect, but they are also more specialised and present knowledge in very narrow topics. Nonetheless, older books and articles can provide valuable information. We often find references to even older basic research which laid the foundations for modern geomagnetobiology or operated in such unique fields that they have never been continued and their results are still valid today. In modern literature we do not find any paper as thorough as Dubrov's 'Geomagnetobiology'. More recent review articles like 'Magnetotactic bacteria, magnetosomes and their application' (Yan et al. 2012) or 'Biological effects of the hypomagnetic field: An analytical review of experiments and theories' (Binhi and Prato 2017) provide more current information, but its form is much more scattered.

Therefore, the main aim of our paper is to present a comprehensive review focused on the impact of the GMF on the origins and evolution of life on Earth, as well as, the influence of the GMF on living organisms at different levels of biological organisation, including the viability of organisms, genetic stability, modulation of gene expression and behaviour. We attempt answer the question: How broad and multi-level is the influence of GMF on living organisms? Such a review should be highly interesting and useful not only for astrobiologists, but also for ecologists, microbiologists, zoologists and botanists.

Survey Methodology

The analysis of changes in the number of papers on GMF-related topics in the WoS and SCOPUS helped us to determine the degree of interest in the topic. However, we did not limit ourselves just to these two databases, but considered many other publications on the GMF and its impact on the origins and evolution of Earth's biosphere. We also referred to the PubMed and Google Scholar. The search strategy included keywords and phrases, such as geomagnetic field, geomagnetism, magnetoreception, hypomagnetic, geomagnetic field AND life on Earth, geomagnetic field AND evolution of life, geomagnetic field AND cells, geomagnetic field AND animals, geomagnetic field AND plants, geomagnetic field AND microfossils, geomagnetic field AND mass extinction. Finally, we considered such books as "The geomagnetic field and life: Geomagnetobiology" by Dubrov (1978), "Young Sun, Early Earth and the Origins of Life" by Gargaud et al. (2012), and online sources of the World Data Centre for Geomagnetism.

Our study focused on papers published between 1960 and 2020, two papers from the first half of 2021, and historical articles and books published between 1953 and 1959.

In our review, we cite in total 165 papers and 8 books. Most papers deal with narrow subject areas concerning one particular group of organisms, e.g. "Magnetoreception in plants" (Galland and Pazur 2005) and "Magnetic orientation in birds" (Wiltschko and Wiltschko 2005) or on specific topics like "Biological effects of the hypomagnetic field: An analytical review of experiments and theories" (Binhi and Prato 2017) and "Biological effects due to weak magnetic field on plants" (Belyavskaya 2004).

The Geomagnetic Field and the Origins of Life on Earth

The geomagnetic field is thought not only to protect life on Earth, but it also may have contributed to its origins, both directly and indirectly. Its indirect role is associated with the stabilising influence on the environment in which life was developing. This includes: protecting the atmosphere and thus maintaining relatively stable environmental parameters, e.g. reduced temperature variation and water in the liquid state, and later the oxidising atmosphere and the ozone layer.

The GMF protects Earth against the solar wind that constantly blows towards it. The solar wind is mainly a stream of ionised hydrogen atoms, protons, and electrons emitted by the Sun (Geiss et al. 1995; Galvin et al. 1996). If it was not for the GMF, the energy carried by wind particles would be transferred directly to the particles of the atmosphere, giving them additional velocity in the anti-sunward direction. As a result, they would be able to overcome Earth's gravity and escape into the interplanetary space, thus depriving Earth of a significant portion of its atmosphere. A similar process may have determined the atmospheres of Venus and Mars. Chemical signatures in these planets' atmospheres imply that at some point they had had atmospheres similar to Earth's, but they changed when lighter elements from their atmospheres (i.e. hydrogen and oxygen) had been lost, probably partially due to the solar wind and the lack of stable, dipole magnetic field similar to the GMF (Luhmann and Bauer 1992; Svedhem et al. 2007; Futaana et al. 2008; Lammer et al. 2018). Dense and rich 'greenhouse gases' in Venus's atmosphere are believed to have lost their lighter elements due to the solar wind (Lammer et al. 2006). Although it is only a speculation, without the GMF, oxygen, which is a gas significantly lighter than carbon dioxide, hydrogen sulphide or other gases in Earth's early atmosphere, would probably be easily blown away by the solar wind as soon as it appeared in the atmosphere. What is more, apart from oxygen, other lighter gases, such as hydrogen and nitrogen, would escape into the space faster than they could be produced by chemical reactions on Earth and in its atmosphere. Only heavier gases, i.e. carbon and sulphur oxides, would be able to stay close to Earth's surface. As a result, Earth's atmosphere would resemble that of Venus (Krasnopolsky and Parshev 1981; Lammer et al. 2006, 2018; Svedhem et al. 2007).

As far as Mars is concerned, its magnetic field is weaker than Earth's, and it exists solely due to the magnetisation of the surface rocks. In fact, it is not a planetary field and as such it lacks a dipole structure which would protect Mars's atmosphere from being blown away. Besides, the smaller mass of the red planet let the solar wind tear the atmosphere easily away, which in turn resulted in the disappearance of surface water bodies. So, had it not been for the protective influence of the GMF, Earth's oxidising atmosphere could not have emerged and persisted. The examples of Venus and Mars show what happens to the atmospheres of planets which did not develop their inner magnetic fields or lost them earlier on.

Moreover, if Earth failed to have the GMF, solar wind particles that reach the atmosphere would react with atmospheric gases, such as molecular (diatomic) nitrogen (N_2) and oxygen (O_2), and thus result in the formation of nitrogen oxide (NO), which would then react with ozone (O_3) (McElroy and McConnell 1971; Revell et al. 2012; Michalski et al.

2014). The product of the reaction, nitrogen dioxide (NO_2), reacts with free radicals of oxygen and forms NO and diatomic oxygen. Eventually, as a result of the decomposition of a single ozone molecule bonded with a single free oxygen atom, two diatomic molecules of oxygen are formed (McElroy and McConnell 1971; Revell et al. 2012; Michalski et al. 2014). In the atmosphere protected by the GMF these reactions also take place, but on a much smaller scale. Most of solar wind particles are deflected from the magnetosphere, and only a small fraction of these highly energetic particles occasionally reaches the atmosphere, igniting the process (Rao 1980). If the GMF was absent, this chain of reactions would continue until the ozone layer was completely destroyed and life with the aerobic metabolism would have no chances to develop (Rao 1980).

The absence of the GMF causes frequent climatic changes that impose severe weather instability. Such a situation happens when there is no GMF and cosmic rays reach Earth. Like the solar wind, cosmic rays consist of high energy particles, consisting of 89% protons, 10% α-particles (helium nuclei), and 1% of other heavy particles (Mewaldt 1996), coming from beyond the Solar System. Among the greatest effects of cosmic rays on the atmosphere there is an increase of ionisation of air particles. The ionisation of lower layers of the atmosphere affects a vertical flow of currents between cloud layers and their electrical potential. This phenomenon results in the formation of ice structures in clouds. Therefore, an increased amount of cosmic rays decreases the amount of solar energy reaching Earth's surface, leading to significant climate cooling. However, the rays are attenuated by magnetic fields of the Sun and Earth, then by Earth's atmosphere, rarely reaching the surface of Earth.

Apart from the above indirect contribution to the origins of life on Earth, the GMF could have also had a direct influence, because the GMF controls the access of cosmic rays and solar wind particles. Both are suspected to be possible energy sources needed for the abiotic formation of biologically significant molecules, and thus indirectly responsible for the initiation of prebiotic evolution (Miller and Urey 1959). In that case, the existence, quality, and strength of the GMF had a prevailing influence on the origins of life on Earth.

The Impact of Earth's Geomagnetic Field on Living Organisms

From the very beginning of their existence, living organisms functioned in the presence of the GMF (Belyavskaya 2004; Borlina et al. 2020) and they need its presence to function properly (Dubrov 1978; Erdmann et al. 2017) on all levels of biological organisation, i.e. cells, tissues, organs and whole organisms.

The GMF, like any other magnetic field, is able to influence, not only ferromagnetic materials like iron, or nickel, but also paramagnets like oxygen, sodium, and diamagnets like zinc, magnesium, copper, phosphorus, water, DNA, many proteins, and even water molecules (Janicki 2008), which are all important for the regulation of cellular processes. Available data including the impact of the GMF's absence, known as hypomagnetic conditions, indicate that the GMF influences: (1) water properties (Janicki 2008); (2) simple and facilitated ion diffusion across membranes (Mika 1996; Zaguła et al. 2011); (3) chromatin condensation (Belyaev et al. 1997); (4) DNA replication (Liboff 1984); (5) gene expression (Blank and Goodman 1997; Mo et al. 2014a); (6) cell cycle (Mo et al. 2013; Surma et al. 2014; Bertea et al. 2015); (7) enzymes activity (Nossol et al. 1993; Zhang et al. 2017) as well as the activity of non-enzymatic proteins including haemoglobin (Janicki 2008) and calmodulin (Markov and Pilla 1994, 1997); (8) the functioning of mitochondria (Fu et al.

2016); (8) cytoskeleton and cell morphology, adhesion, proliferation and migration (Mo et al. 2014b, 2016; Fu et al. 2016), and (9) cell differentiation to, for example, osteoblasts and muscle cells (Surma et al. 2014; Zhang et al. 2014).

The GMF is also important for the functioning of multicellular organism (Fesenko et al. 2010; Mo 2012; Bertea et al. 2015). For instance, cardiovascular and nervous systems have been proven to be most sensitive to changes in the magnetic field. This sensitivity of the cardiovascular system can be explained mainly by the presence of haemoglobin which contains large amounts of iron ions (Janicki 2008). An analysis of medical records indicates that geomagnetic storms, i.e. disturbances in Earth's magnetosphere caused by bursts of radiation and charged particles emitted from the Sun during coronal mass ejection (Andre et al. 1998), may contribute to the myocardial infarction development, although the underlying mechanism may differ for mid- and high latitudes (Samsonov et al. 1960).

First studies on magnetoreception in plants were conducted as early as the mid-twentieth century, however, little is known about their magnetoreception and sensitivity to the GMF when compared to animals and bacteria. Magnetised water facilitates plant growth, increases fertility, and yields a better harvest (Fernandez et al. 1996; Teixeira da Silva and Dobránszki 2014; Abedinpour and Rohani 2017). Studies on the effects of constant and variable magnetic fields on various species of plants, including fruit trees and shrubs, show that seeds germinate faster under the operating field. The GMF also facilitates differentiation of tissues and organs in young plants which leads to an overall faster growth (Rochalska 2007). It has been also demonstrated that even slight changes in the GMF, caused by a modulation of the amount of solar radiation that reaches Earth's surface, may influence the condition of plants. Numerous studies show that magnetic storms have a negative impact on plants as they may lead to anomalies in nucleus and chromosomes, e.g. widespread emergence of cells with polyploid nuclei or the so-called huge nuclei as well as polynucleated cells (Nanush'yan and Murashev 2003). Furthermore, like in animal cells, by modulating ion channels the magnetic field affects the transport of chemical substances between cells as well as the activity of enzymes and the frequency of cell division (Galland and Pazur 2005).

Studies on Life in Hypomagnetic Conditions

The absence or significant weakening of the GMF is called hypomagnetic conditions/hypomagnetic field (HMF) or a Super Weak Magnetic Field (SWMF), however, the terms are not interchangeable. Much research on the effects of hypomagnetic conditions on living organisms was performed in the USA and the former USSR in 1960s and 1970s (Dubrov 1978), and since the early 2000s in other countries, including China, Canada, Japan, Italy, and Romania (Binhi and Prato 2017). Most of the recent studies were summarised and reviewed by Binhi and Prato (2017). The authors showed that a vast majority of studies conducted in hypomagnetic conditions on all sorts of organisms (bacteria, plants, and animals, both vertebrates and invertebrates) demonstrated visible biological effects of hypomagnetic conditions. Their work also implied that those effects were in fact related directly to nonspecific magnetoreception (Binhi and Prato 2017). However, the results of those studies remain ambiguous in some respect. On the one hand, some bacteria species were negatively affected. For example, when colonies of *Staphylococcus aureus* Rosenbach, 1884 were cultured in hypomagnetic conditions, their colony size and number decreased. Other bacteria cultured in hypomagnetic conditions suffered phenotypic changes of shape and size (e.g. *Azotobacter* sp.) accompanied by considerable changes in metabolism (e.g. some *Escherichia coli* Migula, 1895 strains which lost their ability to ferment maltose). On the other hand, the growth of *E. coli* was more rapid in hypomagnetic conditions than in typical magnetic conditions (Dubrov 1978). Besides, *Shigella sonnei* Weldin, 1927 and *Staphylococcus, Salmonella, Klebsiella, Escherichia* species developed antibiotic resistance much faster in hypomagnetic conditions (Dubrov 1978). All in all, it cannot be unequivocally determined if such changes are clearly negative or positive, but definitely they are a reaction to hypomagnetic conditions.

Furthermore, the absence of GMF or weak GMF induces severe dysfunctions in animals, including humans. Research conducted by NASA on mice showed decreased enzyme activity in cells obtained from mice kept in hypomagnetic conditions (Conley 1970). Even earlier before that discovery, there had been speculations that a long-term absence of the magnetic field could cause a serious change in their behaviour (cannibalism) and shorten their lifespan as well as bring about other physiological (infertility) and histological (diffuse tissue hyperplasia) dysfunctions (Dyke 1965; Conley 1969). Further studies also revealed that hypomagnetic conditions could inhibit early embryogenesis (Osipenko et al. 2008a, 2008b) and reproduction capacity (Fesenko et al. 2010), impair learning abilities and memory of adult male mice (Wang et al. 2003), and even inhibit stress-induced analgesia in male mice (Seppia et al. 2000; Prato et al. 2005). Other experiments demonstrated that even a short stay of living organisms in hypomagnetic conditions led to noticeable changes in enzymatic reactions and cell divisions of fibroblasts (Sosunov et al. 1972) as well as animal behaviour, i.e. caused an increase in anxiety among the tested male mice (Ding et al. 2019). Studies on rats indicated that hairs of animals shielded from the GMF contained lower levels of certain elements, such as iron, manganese, copper, and chromium, than hairs of animals not shielded from the GMF (Tombarkiewicz 2008). Finally, an exposure of multiple generations to the hypomagnetic conditions resulted in amnesia of *Drosophila* (*Sophophora*) *melanogaster* Meigen, 1830 (Zhang et al. 2004), whereas chickens needed additional noradrenaline for memory consolidation (Xiao et al. 2009). Even anhydrobiotic abilities of tardigrades were inhibited due to a partial isolation from the GMF (Erdmann et al. 2017). In summary, tardigrades manifested increased mortality after exposure to hypomagnetic conditions (Erdmann et al. 2017, 2021).

The first studies on the influence of hypomagnetic conditions on humans were conducted in the 1960s and concerned the health of astronauts in hypomagnetic conditions in the outer space (Becker 1963; Beischer and Miller 1964; Dubrov 1978). These studies showed changes in calcium homeostasis and circadian rhythms as well as a reduced number of erythrocytes. Subsequent tests revealed that a long-term absence of the magnetic field induced sleep disturbance (Dubrov 1978), thus supporting a hypothesis on the negative impact of the GMF on human health. Other studies specifically targeted to estimate the impact of hypomagnetic conditions on human health showed that a three-day isolation from the magnetic field resulted in decreased metabolism, gastrointestinal diseases and a decrease in the number of leukocytes in blood (Dubrov 1978; Janicki 2008). What is more, such functions of the human brain as learning and memorising were also affected (Binhi and Sarimov 2009, 2013).

Apart from the influence on animal and human cells and tissues, hypomagnetic conditions have a negative influence on the development of plants. For example, hypomagnetic conditions causes characteristic changes in the root meristem in pea (*Pisum sativum* Linnaeus, 1753), common flax (*Linum usitatissimum* Linnaeus, 1753) and lentils (*Lens culinaris* Medikus, 1787). These changes included a partial reduction of the meristem, disruption of protein synthesis and accumulation of lipids as well as a reduction of the organelle's growth, the amount of phytoferritin in plastids and crista in mitochondria (Belyavskaya 2001; Galland and Pazur 2005). All of these changes were accompanied by a more rapid increase of the epicotyl (Negishi et al.

1999). However, it turned out that not all plants reacted in the same extent to a weakened magnetic field. For instance, soya grown in magnetic conditions typical for Mars did not display any changes in water absorption or germination of seeds (Mo et al. 2011). Moreover, seed germination rate of other plants, e.g. French marigold (*Tagetes patula* Linnaeus, 1753), pot marigold (*Calendula officinalis* Linnaeus, 1753), rye (*Secale cereale* Linnaeus, 1753) and alfalfa (*Medicago sativa* Linnaeus, 1753) was the same in hypomagnetic conditions (near zero T) as in the normal GMF (Teixeira da Silva and Dobránszki 2016). On the other hand, seed germination rates of other higher plants, e.g. cabbage (*Brassica oleracea* Linnaeus, 1753), was decreased and seedlings development retarded when exposed to a magnetic field in the range of 100 nT to 0.5 mT (Teixeira da Silva and Dobránszki 2016; Tsetlin et al. 2016). Lastly, there are hardly any studies on the effect of hypomagnetic conditions on fungi and protists (Pazur et al. 2007). One of the few such studies on lower fungi (*Aspergillus* and *Penicillium*) showed no significant changes in their multiplication (Dubrov 1978).

In conclusion, there is no doubt that the HMF has an effect on living organisms, however, no noticeable connection between the magnitude of this effect and physical conditions (field magnitude, magnetic field inhomogeneity, type and duration of exposure) has been found (Binhi and Prato 2017).

Magnetotaxis and Magnetonavigation

Living organisms have many different types of senses depending on stimuli and sources of information. Yet, there are two types of signals that are available in the same extent throughout the globe, i.e. gravity and the GMF. Both are very good sources of information, accessible everywhere, independent from light availability (at night, in oceans depths, underground) or weather conditions. The magnetic field freely penetrates internal organs so an organism's magnetic sense does not require any external sensory organs. Moreover, the GMF sensors can be located in any part of the cell/body, because magnetic energy differs from other energy forms (except gravity) that penetrate tissues only to a specific depth (Mika 1996).

Magnetoreception

Even simple organisms, for example bacteria *Magnetospirillum* sp. (Kirschvink et al. 1985), *Magnetovibrio* sp., and *Magnetococcus* sp. (Yan et al. 2012), and some archaea (Gorobets et al. 2017) can navigate in the magnetic field, an ability known as magnetotaxis (Kirschvink et al. 1985). Bacteria were first described in 1975 to be capable of magnetotaxis, owing to their iron-rich intracellular inclusions (Frankel et al. 1979; Kirschvink et al. 1985). Intracellular inclusions, called magnetosomes, contain magnetite crystals (Fe_3O_4), and to a lesser extent greigite crystals (Fe_3S_4) (Posfai and Dunin-Borkowski 2006; Posfai and Dunin-Borkowski 2009). The greigite-based magnetosomes were reported only in magnetotactic bacteria from anaerobic, brackish and marine aquatic habitats containing significant amounts of H_2S (Pósfai et al. 1998). Both types of crystals have a similar size range from 30 to 120 nm (mostly from 60 to 90 nm), they usually have an elongated shape and contain a single magnetic domain (Pósfai et al. 1998; Posfai and Dunin-Borkowski 2009).

The direction of magnetisation of individual crystals in magnetosomes is defined by the grain size, shape and crystallographic layout. When crystals form a complex system, the strength and direction of their magnetisation is also affected by the neighbouring crystals (Bazylinski and Frankel 2004). It has been observed that bacterial cells closely monitor the layout of crystals in the chain (Simpson et al. 2005). A magnetosome formation process is very complex: it comprises a formation of vesicles, transport of iron, nucleation, growth of magnetite crystals, and finally magnetite crystals connecting into chains (Wang and Liang 2009; Posfai and Dunin-Borkowski 2006). It also involves many proteins which control the process of crystals' nucleation (i.e. MamG, MamF, MamD and MamC proteins) and maintain the correct orientation and function of magnetosomes (MamK and MamJ) (Wang and Liang 2009). In addition, magnetite crystal chains may be embedded in the protein core and surrounded by a phospholipid bilayer, e.g. in bacteria *Magnetospirillum magnetotacticum* Maratea and Blakemore (1981) and *M. gryphiswaldense* Schleifer et al. (1991) (Watanabe et al. 2009). The protein core is formed by cytoskeleton proteins similar to tubulin (Watanabe et al. 2009). There is also a ftsZ-like protein which exhibits high similarities to proteins of several other non-magnetotactic bacterial and Archaean species, i.e., *E. coli*, *Bacillus subtilis* (Ehrenberg, 1835), *B. anthracis* Cohn, 1872 and *Pyrococcus abyssi* Erauso et al., 1993, although it exists in this form only in *Magnetospirillum* strains (Ding et al. 2010). Its exact role is unknown, however, studies showed that disturbances in the formation of magnetosomes were noted in bacteria with mutations in the Fts-Z encoding gene. In this case magnetosomes contained mainly superparamagnetic crystals and had poorly defined morphology (Ding et al. 2010).

There are two different ways which enable magnetotactic bacteria to able detect the magnetic field: axial magnetoreception and polar magnetoreception. For example, the *M. magnetotacticum* AMB-1 strain shows axial magnetoreception, which means that it passively orientates itself on the magnetic field and may actively move along the lines of force of the magnetic field in both directions from the magnetic pole to the magnetic equator although without any preference towards the magnetic north or south. Conversely, the *Magnetococcus* sp. MO-1 strain displays polar magnetoreception, so it moves parallel to the lines of the field (to the north magnetic pole, i.e. to south) or antiparallel (going up to the south magnetic pole, i.e. to north), thereby showing preference towards polarity (Lefevre et al. 2009). A single cell equipped with one or more magnetosomes can be regarded as a magnetic dipole, akin to a compass needle with a magnetic moment. The GMF acting on such a dipole generates a torque. As long as the magnetic energy of such a cell is at least ten times larger than its thermal energy, the cell will be directed according to the external magnetic field, which is sufficient for effective navigation in Earth's magnetic field (Bazylinski and Frankel 2004).

Magnetosomes were also found in some single-cell eukaryotes, such as *Phytoflagellata* and *Anisonema* (Euglenophyceae). Their cells contain thousands of magnetite crystals, which are very similar to those in magnetotactic bacteria. However, the origin of these magnetosome-like structures is still unknown. It is presumed that some protists are able to perform biomineralisation of endogenous magnetic particles. On the other hand, several observations indicate that some of them do not have this ability and absorb crystals from magnetotactic bacteria which they consume (Torres de Araujo et al. 1986; Bazylinski et al. 2000; Galland and Pazur 2005).

Magnetofossils, i.e. magnetite nanocrystals of organic origins, are found in rocks of various ages. Presumably, the oldest fossils of this type come from layers formed 2.8 billion years ago (Kopp and Kirschvink 2008). Their shape, size and morphology resemble bacterial magnetosomes (Gehring et al. 2011; Chang et al. 2012). The fact that these advanced magnetically sensitive structures are present both in present-day and prehistoric bacteria may indicate that magnetoreception is indeed a very early adaptation.

The first animals found to have the ability of magnetonavigation were birds, i.e. the European robin (*Erithacus rubecula* (Linnaeus, 1758)) (Wiltschko and Merkel 1966). Since then, this ability has been confirmed to be present in Platyhelminthes, molluscs, crustaceans, insects and all groups of vertebrates (Wiltschko and Wiltschko 2005; Johnsen and Lohmann 2008; Wajnberg et al. 2010; Ernst and Lohmann 2016; Mouritsen 2018; Yosef et al. 2020). In fact, ecological and behavioural aspects of the use of the magnetic field as a source of information have been studied fairly well. Two mechanisms have been described that can help to explain magnetoreception in animals, i.e. the Magnetite-Based Mechanism (MBM) and the Radical Pair Mechanism (RPM).

The MBM is based on magnetite lumps (Malkemper et al. 2016) and it is very similar to magnetosomes found in bacteria. Various structures can play a role of the MBM detector, from magnetite crystals with a single magnetic domain or multidomain crystals to small crystals with superparamagnetic properties. Single-magnetic domain crystals were found, for example in honey bees (*Apis mellifera* Linnaeus, 1758) (Wajnberg et al. 2010), chitons (Lowenstamm 1962) and Osteichthyes (Wiltschko and Wiltschko 2006). In cetaceans, apart from single-domain crystals, multidomain crystals were also found (Posfai and Dunin-Borkowski 2009). Tiny crystals with superparamagnetic properties have been observed in nematodes, termites, doves, cetaceans and humans (Kirschvink et al. 1992; Cranfield et al. 2004; Posfai and Dunin-Borkowski 2009). Like in the case of bacteria, magnetite is not the only mineral used in animal magnetoreception, because maghemite (γ-Fe_2O_3) crystals were found in homing pigeons and even humans (Frankel et al. 1979). Moreover, also particles of hematite (Fe_2O_3) were found in humans, however their function remains unknown (Posfai and Dunin-Borkowski 2006).

Posfai and Dunin-Borkowski (2009) suggested that the magnetoreception system of animals resembled chains of single-magnetic domain crystals recognised in bacteria. According to these authors, the magnetic field opens ion channels by deflection of the chains, thus leading to depolarisation of the cellular membrane and transmission of signals to the brain (Walker et al. 2002). However, other authors claim that magnetoreception is possible due to a system of superparamagnetic crystals with dimensions of 2–5 nm that do not have a permanent magnetic moment (Davila et al. 2003). These crystals are located in vesicles which change their shape in the presence of a constant magnetic field. Due to such deformation, the vesicles attract or repel each other, leading to a deformation of the membrane to which they are attached. So, it causes an opening of ion channels transmit signals to the central nervous system (Davila et al. 2003).

The RPM appears to be evolutionarily younger than the MBM (Malkemper et al. 2016). It is responsible for a more advanced system of magnetoreception, which enables animals to determine the direction and position of the poles as well as construct a magnetic map in their memory. This mechanism was taken into consideration when it turned out that birds' spatial orientation was impaired when they had one eye covered (especially the right one). Accordingly, it was concluded that the location of the magnetic sense of those animals may be associated with the structure of their eyes (Wiltschko and Wiltschko 2006). Studies from the 1970s and 1980s addressed a hypothesis formulated by Schulten et al. (1978) that assumed that in some organisms, including birds, there must be a chemical compound that reacted both to light and the magnetic field (Schulten and Windemuth 1986). Further research confirmed that cryptochromes, special pigments located in the retina, were responsible for that process (Ritz et al. 2000; Hand 2016; Pinzon-Rodriguez and Muheim 2017). These pigments are common, as Schulten et al. (1978) suspected, in the eyes of many animal species, including humans (Foley et al. 2010).

Cryptochromes are flavoproteins containing flavin adenine dinucleotide (FAD) They are members of the same family of proteins as photolyases (Hore and Mouritsen 2016). Due to a reaction triggered by green, blue or UV light, cryptochromes absorb a quantum of light, and a pair of free radicals is formed, comprising FAD and one of the protein amino acids (Biskup et al. 2009; Zhang et al. 2015). Then, a conversion between singlet and triplet states occurs and this process is modulated by the magnetic field. The direction of the field's line of induction relative to the position of molecules conditions the parallel orientation of spins for the triplet state and antiparallel for the singlet state. Thus, a formed pair of radicals with a given spin participates in a reaction whose final product is dependent on the spin direction (Wiltschko and Wiltschko 2006). In the case of animals having cryptochromes in their eyes, it may be concluded that the role of the GMF is visible. It is assumed that radical pair singlet and triplet states influence a transfer of stimuli from the eye to the central nervous system and/or these products modify the sensitivity of light-sensitive receptors. Consequently, information reaching the brain is distorted, and it may cause changes in the brightness of a given location depending on the position of the animal's eyes relative to the lines of the GMF (Pinzon-Rodriguez and Muheim 2017; Ritz et al. 2002; Juutilainen et al. 2018).

Animals use their senses like a compass to detect the GMF axis and determine directions. Research show that there are two types of the magnetic compass, i.e. an inclination compass and a polar compass (Wiltschko and Wiltschko 2006). They detect various properties of the GMF and follow different magnetoreception mechanisms (Wiltschko and Wiltschko 2005; Wajnberg et al. 2010). The inclination compass is sensitive to light, so it is connected with the presence of the RPM, whereas the polar compass is insensitive to light and therefore must use other mechanisms of magnetoreception, probably related to the MBM (Ritz et al. 2002; Wajnberg et al. 2010). To determine directions, the inclination compass uses the angle between the geomagnetic vector and the surface of the planet. It is worth noticing that animals which use this type of compass do not differentiate between north and south, but only between the direction 'to the pole' and 'to the equator'. Therefore, changes in the vertical or horizontal component of the GMF cause changes in movement directions (Wiltschko and Wiltschko 1996). Animals which use the inclination compass include insects, amphibians, sea turtles (Lohmann 1991; Lohmann and Lohmann 1993) and birds (Wiltschko and Wiltschko 2006; Vacha et al. 2008). The polar compass, which is based on the perception of the horizontal component of the GMF, does not sense changes in the vertical component. So, animals which use it, can differentiate between the north and the south pole (Wiltschko and Wiltschko 1996). This group features crustaceans, bony fish, and mammals (Lohmann et al. 1995; Wiltschko and Wiltschko 2006). However, during long-distance migrations, the magnetic compass alone is often insufficient for accurate navigation. It has been confirmed that both the inclination and the intensity of the GMF in a given place on Earth may constitute a source of information for the animal on its exact location (Lohmann et al. 2007). In a way, this natural navigation system may provide animals with information on their geographic location and help them choose the correct route to the destination. This type of navigation is often called a magnetic map, but some scientists consider the term to be vague and misleading (Lohmann et al. 2007). Many animals that use magnetic maps, e.g. salmons (Putman et al. 2013, 2014a, 2014b; Scanlan et al. 2018; Lohmann and Lohmann 2019) and sea turtles (Lohmann et al. 2001, 2004, 2012; Putman et al. 2011; Lohmann and Lohmann 2019) are able to periodically update their magnetic map in vital areas, i.e. nesting sites, while visiting them, and thus avoid or reduce the number of errors that might occur due to the secular variation (Brothers and Lohmann 2015; Lohmann and Lohmann 2019). Although little is still known what operational principles these systems adhere to, it is assumed that there are various types of magnetic maps, for example one- and two-dimensional. One-dimensional maps are simpler and based on changes of only one parameter of the GMF, either inclination or intensity. However, in favourable conditions, the map may be sufficient for locating any point on Earth (Lohmann and Lohmann 2006) and some sea turtles are thought to be using this type of magnetic map (Lohmann et al. 2007). Two-dimensional maps are based on both parameters (inclination and intensity) simultaneously. Moreover, some animals may use different magnetoreception strategies at different stages of their lives. For instance, young turtles, *Caretta caretta* (Linnaeus 1758) are believed to use two- dimensional magnetic maps based on a system of magnetic orientation points of a given/relevant inclination and intensity. On the other hand, mature turtles use one-dimensional map and move along isolines of the GMF until they reach their destination (Lohmann et al. 2007). Nevertheless, it should be remembered that most animals probably do not see any map image; instead, they compare the intensity and/or inclination of the GMF in a given place with the data of their destination (Lohmann et al. 2007).

Animal Magnetonavigation

Regardless of which map animals use, one- or two-dimensional, they navigate in three different ways. Firstly, they move towards a known point according to the gradient of the inclination and/or intensity of the GMF, e.g. young green sea turtles (*Chelonia mydas* Linnaeus, 1758) (Avens and Lohmann 2004; Lohmann and Putman 2007), and the Caribbean spiny lobster (*Panulirus argus* Latreille, 1804) (Boles and Lohmann 2003; Lohmann et al. 2007). Secondly, they find an isoline and move along it until they find the desired location, e.g. sea turtles (Lohmann et al. 2007, 2008; Brothers and Lohmann 2015). Finally, some animals may also utilise the strategy of moving according to orientation points, i.e. areas with remembered parameters of the GMF, where they change the direction of the movement, e.g. nightingales *Luscinia luscinia* (Linnaeus, 1758; Fransson et al. 2001; Kullberg et al. 2003; Lohmann et al. 2007) and rock pigeons *Columba livia* Gmelin, 1789. For short distances, rock pigeons use orientation points they know and move along known routes, even if they are longer than the optimal way (Biro et al. 2004). On top of that, some animals combine two of these scenarios. For example, the European pied flycatcher *Ficedula hypoleuca* (Pallas, 1764) uses orientation points on the route from Central Europe to Spain, and it changes the direction and goes towards a known point in the Central Sahara according to the gradient of the inclination and/or intensity of the field (Lohmann et al. 2007).

Magnetonavigation is also used at different distances. Long-distance navigation was studied on monarch butterflies *Danaus plexippus* (Linnaeus, 1758) (Wajnberg et al. 2010), sharks (Klimley 1993), sockeye salmons *Oncorhynchus tnerka* (Walbaum, 1792) (Walker 1997) and robins (Wiltschko and Merkel 1966). Also, cetaceans determine directions during their long migrations using the GMF (Walker 1992). Then, shorter distances are covered by the Caribbean spiny lobster (Boles and Lohmann 2003; Lohmann et al. 2007), ants *Pachycondyla marginata* Roger, 1861 (Wajnberg et al. 2010) and the salamander *Notophthalmus viridescens* (Rafinesque, 1820) (Fisher et al. 2001; Phillips et al. 2002; Lohmann et al. 2007).

Yet, the magnetic sense does not have to be connected only with migrations. For example, mammals from the family Spalacidae, *Spalax ehrenbergi* (Nehring, 1898), and mole rats from the genus *Cryptomys* which spend most of their life underground, use navigation to move inside their burrows (Kimchi et al. 2004), while honey bees use magnetic stimuli as a source of information on the location of food sources, and worker bees are able to pass this information to one another and such a transfer most probably also includes the GMF data (Wajnberg et al. 2010). An interesting example is also magnetic alignment, which means that an animal aligns its body axis with the lines of the GMF, as it was observed in many invertebrate and vertebrate species. This intriguing behaviour is demonstrated by animals very well-known for their magnetonavigation abilities, such as birds (Bianco et al. 2019), but also many species of mammals whose magnetonavigation abilities have not been considered, yet. For instance, cattle, the European roe deer and red deer position themselves along the north–south axis when resting or feeding (Begall et al. 2008; Burda et al. 2009; Slaby et al. 2013; Belova and Acosta-Avalos 2015). Similarly, dogs align their body along the north–south axis during defecation (Yosef et al. 2020). In fact, numerous studies show that among vertebrates magnetic alignment behaviour typically coincides with the north–south magnetic axis, but mean directional preferences of animals are often rotated clockwise from the north–south axis (Malkemper et al. 2016; Červený et al. 2011; Begall et al. 2013; Hart et al. 2013). Still, mechanisms of this phenomenon and its possible adaptive significance remain unknown (Malkemper et al. 2016). Also, research reveal that animals use the GMF to some degree when they select locations for their lairs and rutting (Tombarkiewicz et al. 2010). It has also been proven that deer, wild boars and otters prefer areas free of the GMF disturbances for their lairs and burrows. On the other hand, badgers select areas of the inhomogeneous magnetic field for their burrows (Tombarkiewicz et al. 2010), whereas it is suggested that compass termites (*Amitermes meridionalis* Froggatt, 1898) may build and repair their mounds by using magnetic cues (Jacklyn and Munro 2002).

Magnetoreceptors have been noticed in many species that do not display behaviour dependent on the GMF. Magnetite, maghemite and hematite crystals (see section 'Magnetoreception') have also been discovered in the human brain (Yang et al. 2017; Gorobets et al. 2017; Posfai and Dunin-Borkowski 2009), and cryptochromes (see section 'Magnetoreception') in retina (Kirschvink et al. 1992). These magnetoreceptors have been confirmed to be active (Foley et al. 2010), however, their purpose remains yet to be addressed (Nishimura et al. 2014).

In conclusion, most animals, if not all, including humans possess at least one of the above magnetoreception mechanisms which enable or can enable magnetonavigation. According to the available data, animals use their magnetoreceptors to a different extent, but the very fact they exist means that the GMF detection is very important.

Magnetoreception of Plants and Fungi

Currently, plant magnetoreception mechanisms are thought to be similar to those found in animals, i.e. magnetoreception based on the presence of ferromagnetic crystals (MBM) or the RPM connected with the presence of cryptochromes. Besides, a mechanism based on ion cyclotron resonance is proposed as an alternative explanation of magnetoreception in plants (Galland and Pazur 2005).

An example of plant magnetoreception is demonstrated by roots of some plants which are oriented along the east–west axis. Wheat (*Triticum aestivum* Linnaeus, 1753) roots grow parallel to the horizontal component of the GMF, whereas storage roots of beet (*Beta vulgaris* Linnaeus, 1753) grow in the direction of the GMF activity (Galland and Pazur 2005). Then, it has been shown that seeds placed with their longer axis parallel to the lines of the GMF germinate and grow faster (Kobayashi et al. 2004), e.g. barley (*Hordeum vulgare*

Linnaeus, 1753), common flax, oat (*Avena sativa* Linnaeus, 1753), rye, maize (*Zea mais* Linnaeus, 1753), pea, and wheat (Galland and Pazur 2005; Pittman 1963).

In the case of magnetoreception and magnetonavigation in fungi little is known and studies on this topic have been extremely limited (Pazur et al. 2007).

The Impact of the Geomagnetic Reversal

The GMF has properties of a constant field; however, it undergoes periodic changes. These include temporary disturbances caused by magnetic storms as well as long-term alternations, e.g. a drift of geomagnetic poles (Dubrov 1978; World Data Center for Geomagnetism 2012; Livermore et al. 2020). It also experiences changes in the location of the magnetic poles, called the geomagnetic reversal (GMF reversal) or polarity reversal, which occur every several dozen thousands to several million years (Dubrov 1978, Prévot et al. 1985, Panovska et al. 2019). Though it has never happened during the existence of human civilisation, other hominids were witnesses to the last GMF reversal nearly 780 thousand years ago (Panovska et al. 2019).

We do not know the exact nature of the GMF reversal. The only remnants of this phenomenon are paleomagnetic records in the rocks. There are many hypotheses and theoretical models. Most of them suggest that the GMF reversal is a slow phenomenon lasting from 2,000 to 12,000 years, on average ca. 7000 years (Glassmeier and Vogt 2010; Clement 2004; Glatzmaier and Coe 2015). Some models assume that during the GMF reversal, Earth's magnetic field decreases to ca. 10% of its current value (Glassmeier and Vogt 2010), because its internal component, whose GMF value amounts to 90–95%, disappears.

It is worth noticing that not all of polarity changes are fully stable, as soon after the reversal the GMF returns to its previous polarity. Owing to such instabilities, some scientists classify those events as geomagnetic excursions, not as the GMF reversals (Panovska et al. 2019). Geomagnetic excursions are relatively short (a few hundred to more than 10 thousand years) changes in the field intensity of low latitude (up to 45° from the previous position) or even full reverses, but with the GMF returning to its previous polarity (Panovska et al. 2019). Although the mechanisms driving the excursions and their relation to the GMF reversals are not fully understood, their 'rapid' nature makes them potentially harmful to life (Cooper et al. 2021).

The question is whether the GMF reversal can affect life on Earth. As early as in 1963, it was postulated by Uffen (Uffen 1963) that the weakening of the GMF would release particles trapped in the Van Allen radiation belts, which would strike Earth's surface directly, and thus bring about changes and instability of the atmosphere. This would trigger significant climate change and destabilisation of the ozone layer, which would lead to an increase of ionizing radiation including the UV radiation (Valkovic 1977). Also, because of the overall impact of the GMF on living organisms, a majority of the GMF changes would lead to a long-term deterioration of individual organisms' health. Additionally, a lack of inverted magnetic poles could be problematic for organisms which use the GMF for navigation as their migration could be disturbed.

Yet, another question arises whether the GMF reversal could affect the health of individual specimens as well as entire populations, and eventually cause mass extinction, as some scientists suggest. Regretfully, there is no satisfactory answer. The GMF reversal is an environmental change of an enormous scale, and definitely it can impact many elements of the biosphere. Historically, some GMF reversals were believed to be followed by the emergence of new groups of organisms (Glassmeier and Vogt 2010), and several mass extinctions can be attributed to the GMF reversal, e.g. the Cretaceous-Paleogene mass extinction coincided with the GMF reversal (Crain 1971), however, Glassmeier and Vogt undermine the validity of such correlations (Glassmeier and Vogt 2010). In more recent studies new interconnection were noted. Wei and colleagues suggested a possible link between the increase of the GMF reversal frequency, observed decrease in oxygen level and marine species extinctions (Wei et al. 2014). Similarly, the Ediacaran extinction event is believed to have been caused by the GMF reversal (Meert et al. 2016). Present-day studies imply that geomagnetic excursions, e.g. Laschamp excursion (41 to 42 thousand years ago) and excursions identified in sediments of Brunhes Chron (nearly 13 thousand years ago) could have led to a regional extinction of large mammals (Channell and Vigliotti 2019). According to Cooper et al. (2021), the Laschamp excursion in combination with the Grand Solar Minima, initiated substantial changes in the concentration and circulation of the atmospheric ozone, increased atmospheric ionisation and ultraviolet (UV) radiation levels, leading to global climate shifts that caused major environmental changes. It was also suggested that those environmental changes could have sparked a chain of events leading to the extinction of large mammals in Australia and Europe, and possibly to the extinction of *Homo neanderthalensis* (King 1864) and subsequent success of *Homo sapiens* Linnaeus 1758 (Channell and Vigliotti 2019; Cooper et al. 2021). Similarly, large mammals' extinctions in North America and Europe 13 thousand years ago could be linked to geomagnetic excursions identified in sediments of Brunhes Chron.

Truth be told that even with these new premises, we still operate more in the realms of speculation. The existence of a link between polarity transitions and mass extinctions is possible, and the topic is worthy of a debate, however, new multidisciplinary studies are indispensable if we want to come closer to the final conclusion.

Implications for Astrobiology

A comparison between Earth and its two neighbouring rocky planets makes us fully aware of why astrobiologists assume that the planet's possession of a stable planetary magnetic field (PMF) is considered to be a key factor determining the habitability of the very planet (Lammer et al. 2009; Cuartas 2018).

Planetary habitability is a measure of a celestial body's ability to provide conditions suitable for the emergence and maintenance of life on its surface (Meadows and Barnes 2018). There are many factors influencing habitability of a planet (Papagiannis 1992; Lammer et al. 2009): ranging from proper characteristics of the parenting star, the mass and size of the given celestial body, its distance from the star and its spinning rate, to plate tectonics and properties of the atmosphere (Papagiannis 1992; Lammer et al. 2009). However, five features seem to be the most essential for the origins and development of life: most importantly liquid water (Meadows and Barnes 2018), ensured by stable temperatures, atmosphere, sources of energy and nutrients (Papagiannis 1992; Meadows and Barnes 2018). At least three of these features seems to be more likely to find on planets with the stable PMF (in the case of Earth the GMF), like it was shown by comparison of Venus, Earth, and Mars (see section 'The geomagnetic field and origins of life on Earth'). Still, the problem is that unlike planets and moons of our Solar System, whose PMFs have been measured to some extent (Bland et al. 2008), exoplanets are currently impossible to be studied with regard to direct measurements of their PMFs, therefore precise predictions of structure and the source of energy of those PMF are impossible to make (Cuartas 2018). So, to prepare models of those celestial bodies' PMFs, some suppositions in terms of the possible composition and structure should be considered (Cuartas 2018; Zuluaga and Bustamante 2018).

Another issue that needs addressing from the point of view of astrobiology and future space missions is how terrestrial life could survive while living in magnetic conditions different from the GMF, e.g. in hypomagnetic conditions. Should Earth's organisms, simple or complex, be able to survive in hypomagnetic conditions, manned space flights and planetary protection policies would be affected (Erdmann et al. 2021). In this context, studies on the influence of the GMF and/or hypomagnetic conditions on Earth's organisms (especially extremophiles) is of high importance (Erdmann et al. 2021).

Conclusions

The geomagnetic field (GMF) protects Earth from the solar wind and cosmic rays. In this way it helps to maintain Earth's atmosphere and the ozone layer, ultimately stabilising conditions on our planet and regulating the amount of energy reaching its surface. The influence of the GMF on living organisms cannot be underestimated, because they are negatively affected by hypomagnetic conditions. Organisms developed magnetoreception on the basis of the radical pair mechanism (RPM), and therefore the GMF has become an exceptional source of positional information. Thanks to this ability, organisms are able to find most convenient habitats and rutting places not to mention migrations over huge distances.

Finally, the nature of the GMF enabled and enhanced the evolution of life on Earth. Apart from gravity, the GMF was the only relatively invariable aspect of the environment for the first organisms emerging amid dynamic changes on Earth. This notion is proved by the fact that magnetoreceptors or their relics are widespread among many organisms.

To conclude.

1. The GMF directly shields Earth from corpuscular radiation, i.e. the solar wind and cosmic rays.
2. The GMF shields Earth indirectly, by stabilising its atmosphere and the ozone layer.
3. There is a considerable body of evidence that many organisms interact with the GMF on the basis of nonspecific magnetoreception, which occurs in cells, tissues, organs, systems, as well as whole organisms.
4. Apart from gravity, the geomagnetic field is the only ubiquitous and relatively permanent element of the environment, thus being a great source of information for organisms.
5. Long-term changes in the GMF could shape environmental changes, and therefore influence the rate of evolution. Still, new multidisciplinary studies ought to be carried out in this area.

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