The physics of hypomagnetic field effects in the radical pair mechanism

Hadi Zadeh-Haghighi1,2,3,* , Rishabh1,2,3, and Christoph Simon1,2,3,*

1Department of Physics and Astronomy, University of Calgary, Calgary, AB, T2N 1N4, Canada
2Institute for Quantum Science and Technology, University of Calgary, Calgary, AB, T2N 1N4, Canada
3Hotchkiss Brain Institute, University of Calgary, Calgary, AB, T2N 1N4, Canada

* hadi.zadehhaghighi@ucalgary.ca & csimo@ucalgary.ca

ABSTRACT

Near-zero magnetic fields, called hypomagnetic fields, are known to impact biological phenomena, including developmental processes, the circadian system, neuronal and brain activities, DNA methylation, calcium balance in cells, and many more. However, the exact mechanism underlying such effects is still elusive, as the corresponding energies are far smaller than thermal energies. It is known that chemical reactions involving radical pairs can be magnetic field dependent at very low intensities comparable to or less than the geomagnetic field. Here, based on the spin dynamics of the radical pairs, we present a theoretical and numerical analysis of the hypomagnetic field effects. We conclude that the geomagnetic field may be essential for biological processes via quantum effects, and that hypomagnetic field effects are a particularly promising avenue for testing the radical pair mechanism.

Keywords: hypomagnetic field effects in biology, radical pair mechanism, quantum spin, spin chemistry

1 Introduction

Weak magnetic field effects are widespread in biology1. The strength of the magnetic field in such phenomena can go below the magnitude of the geomagnetic field. Hypomagnetic fields, which are near-zero fields and can be produced by shielding the earth’s magnetic field, are also known to impact biological functions2–9. Such effects have been observed in genetics, developmental processes, the circadian clock, neurons and the brain, and so forth. It has also been suggested that extinction events on Earth10 may be related to the changes in geomagnetic field11. Early studies, motivated by the concerns around the health of astronauts in outer space, concluded that exposure to hypomagnetic fields had adverse effects on human health12–15. Apart from hypomagnetic field effects on animal and human cells and tissues, deprivation in geomagnetic field can influence the development of plants as well8,9. It, therefore, seems pertinent to conclude that the geomagnetic field may play essential roles in living organisms, and diminishing it or making it disappear could result in adverse consequences.

Earth’s magnetic field, depending on latitude, ranges from ∼24 to ∼66 µT16, which is hundreds of times smaller than the strength of a typical refrigerator magnet. Remarkably, the scale of energies corresponding to the geomagnetic field is about a million times smaller than thermal energies, $k_B T$ ($k_B$ and $T$ are the Boltzmann constant and temperature, respectively), at biologically relevant temperatures. Thus far, the mechanisms behind such effects remain elusive.

It is known that applied magnetic fields can influence reaction rates and yields in certain chemical reactions17–19. The key elements in these processes are pairs of radicals—transient molecules with an odd
number of electrons in their outer shell—that carry quantum spins. Electrons possess spins of \( S = \frac{1}{2} \). Spin also has a magnetic feature, meaning that any other spins and magnetic field around can influence the spin state of the particle (radical). A pair of radicals can be formed by electron transfer between two molecules or breaking a chemical bond. A radical pair can be in a singlet or triplet state, depending on the donor and acceptor molecule’s spin configuration\(^{20}\). Spin is usually a conserved quantity in reactions involving organic molecules, which is essential for magnetic field effects in biochemical reactions involving radical pairs\(^{21}\). In other words, depending on the spin state of the radical pair, the chemical process will take either singlet or triplet paths, which will result in different chemical yields.

It has been proposed that the radical pair mechanism underlies many magnetic field effects across biology\(^1\). Previously, radical pair models have been proposed for avian magnetoreception\(^{22}\), isotope effects on xenon anesthesia\(^{23}\) and lithium effects on mania\(^{24}\), and magnetic field effects on the circadian clock\(^{25}\). In recent studies, it is also suggested that radical pairs may explain hypomagnetic field effects on hippocampal neurogenesis\(^{26}\) and microtubule reorganization\(^{27}\). However, the physical mechanisms behind these effects are incompletely understood. Here, based on the radical pair mechanism, we present an analytical and numerical analysis of the hypomagnetic field effects. We show that within a reasonable range of parameters, the hypomagnetic field effects emerge naturally from the spin dynamics of the radical pairs. Lastly, we propose that hypomagnetic field effects are particularly a promising way of testing radical pair models.

2 Results

2.1 Spin dynamics

In a radical pair, coupling of two electron spins, \( S_A \) and \( S_B \), results in a total spin of \( S_T \), which has a quantum number of either \( S = 1 \) or \( S = 0 \). The latter is a singlet state, with \( m_s = 0 \), and the former is a triplet state, with \( m_s = 0, \pm \frac{1}{2} \). \( m_s \) describes the projection of the magnetic quantum number onto a fixed axis.

\[
|S\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle_A \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_B) ,
\]
\[
|T_-\rangle = |\downarrow\rangle_A \otimes |\downarrow\rangle_B ,
\]
\[
|T_0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle_A \otimes |\downarrow\rangle_B + |\downarrow\rangle_A \otimes |\uparrow\rangle_B) ,
\]
\[
|T_+\rangle = |\uparrow\rangle_A \otimes |\uparrow\rangle_B ,
\]

where \( \otimes \) is the tensor product. \( |T_-\rangle, |T_0\rangle, \) and \( |T_+\rangle \) are the triplet states. \( |S\rangle \) is known as the singlet state.

Starting from a singlet state, the initial spin density matrix for the radical pair reads as follows:

\[
\hat{\rho}(0) = \frac{1}{M} \hat{\rho}^S ,
\]

and for triplet initial state:

\[
\hat{\rho}(0) = \frac{1}{3M} \hat{\rho}^T ,
\]

where

\[
\hat{\rho}^S = |S\rangle \langle S| \otimes \hat{I}_M ,
\]
\[ \hat{P}^T = \{ |T_+\rangle \otimes \langle T_+ | + |T_0\rangle \otimes \langle T_0 | + |T_-\rangle \otimes \langle T_- | \} \otimes \hat{1}_M, \] (8)

\[ \hat{P}^S + \hat{P}^T = \hat{1}_{4M}, \] (9)

\[ M = \prod_i^n (2I_i + 1). \] (10)

Here \( \hat{P}^S \) and \( \hat{P}^T \) are the singlet and triplet projection operators, respectively, \( M \) is the nuclear spin multiplicity, \( I_i \) is the spin angular momentum of \( i \)-th nucleus, and \( \hat{1}_n \) is the \( n \times n \) identity matrix.

For studying the spin dynamics of the radical pairs, it is essential to consider the interactions between the unpaired electron spins on each radical with each other, surrounding nuclear spins, and external magnetic fields. All these interactions can be included in the Hamiltonian of the system, \( \hat{H} \). The next step is solving the density matrix equation:

\[ \frac{d\hat{\rho}(t)}{dt} = -i\hbar [\hat{H}, \hat{\rho}(t)], \] (11)

where \( \hat{\rho}(t) \) and \( \hat{H} \) are the spin density and Hamiltonian operators, respectively, \( i \) is the imaginary unit and \( \hbar \) is the reduced Planck constant. \([\cdot,\cdot]\) denotes the commutator.

For simplicity, let us consider only the isotropic hyperfine (\( \hat{H}_{HF} \)) and Zeeman (\( \hat{H}_Z \)) interactions. We neglect dipolar and exchange interactions; it should be noted that including these terms in the model can reduce the magnetic field sensitivity\(^{26,29} \). However, this may be compensated by potential amplification effects in the biological systems\(^{25,30} \). Of note, the anisotropic components of the hyperfine interactions are only relevant when the radicals are aligned and immobilised\(^{31} \). The Hamiltonian for this system reads as follows:

\[ \hat{H} = \hat{H}_Z + \hat{H}_{HF} = -\gamma_e h (\hat{S}_A + \hat{S}_B) \cdot \mathbf{B} + \sum_{iA} a_{iA} \hat{S}_A \hat{I}_{iA} + \sum_{iB} a_{iB} \hat{S}_B \hat{I}_{iB}, \] (12)

where \( \gamma_e, h, \hat{S}_{A/B}, \mathbf{B}, a_{iA/B}, \hat{I}_{iA/B}, \) and \( N_{A/B} \) are the electron magnetogyratic ratio, the Planck constant, the spin operators of electron A/B, the magnetic field, the isotropic hyperfine coupling constants for electron A/B, nuclear spin of \( i \)-th nucleus for electron A/B, and number of nuclear spins coupled to electron A/B, respectively.

Let us consider a minimal model comprising two electron spins, \( A \) and \( B \), where \( A \) is coupled to a spin-1/2 nucleus, \( \hat{S}_A \otimes \hat{I}_A \otimes \hat{S}_B \). In this case, the Hamiltonian has the following form:

\[ \hat{H} = \begin{pmatrix}
\frac{a}{4} + B & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{a}{4} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{a}{4} + B & 0 & \frac{a}{2} & 0 & 0 \\
0 & 0 & 0 & \frac{a}{4} - B & 0 & \frac{a}{2} & 0 \\
0 & \frac{a}{2} & 0 & -\frac{a}{4} & 0 & 0 & 0 \\
0 & 0 & \frac{a}{2} & 0 & -\frac{a}{4} - B & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{a}{4} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{a}{4} - B
\end{pmatrix}, \]
where $a$ is the hyperfine coupling constant and $B$ is the applied magnetic field. The normalized eigenstates of this system, $\psi_i$, are the following:

\[
\begin{align*}
\psi_1 &= |\uparrow\rangle_A \otimes |\uparrow\rangle_N \otimes |\uparrow\rangle_B, \\
\psi_2 &= |\uparrow\rangle_A \otimes |\downarrow\rangle_N \otimes |\downarrow\rangle_B, \\
\psi_3 &= \frac{\alpha}{\xi} |\uparrow\rangle_A \otimes |\downarrow\rangle_N \otimes |\uparrow\rangle_B + \frac{2a}{\delta} |\downarrow\rangle_A \otimes |\uparrow\rangle_N \otimes |\downarrow\rangle_B, \\
\psi_4 &= \frac{1}{\sqrt{5}} |\uparrow\rangle_A \otimes |\downarrow\rangle_N \otimes |\uparrow\rangle_B - \frac{2\text{sgn}(\alpha)}{\sqrt{5}} |\downarrow\rangle_A \otimes |\uparrow\rangle_N \otimes |\downarrow\rangle_B, \\
\psi_5 &= \frac{a}{2\xi} |\uparrow\rangle_A \otimes |\downarrow\rangle_N \otimes |\uparrow\rangle_B - \text{sgn}(\nu) |\downarrow\rangle_A \otimes |\uparrow\rangle_N \otimes |\downarrow\rangle_B, \\
\psi_6 &= 2 \frac{\sqrt{2}}{\sqrt{5}} |\uparrow\rangle_A \otimes |\downarrow\rangle_N \otimes |\uparrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_N \otimes |\downarrow\rangle_B, \\
\psi_7 &= |\uparrow\rangle_A \otimes |\downarrow\rangle_N \otimes |\uparrow\rangle_B, \\
\psi_8 &= -\text{sgn}(\alpha) |\downarrow\rangle_A \otimes |\downarrow\rangle_N \otimes |\downarrow\rangle_B.
\end{align*}
\]

where $\alpha = B - \frac{a}{4}$, $\xi = \sqrt{\alpha^2 + \frac{a^2}{4}}$, $\delta = \sqrt{\alpha^2 + 4a^2}$, and $\eta = 4B - 3a$.

In this simple model, assume the radical pairs are initially in a singlet state, and the nuclear spin is up (In the rest of this paper and in the expression for the singlet yield in this section, the initial nuclear states are averaged over):

\[
\frac{1}{\sqrt{2}} \left( |\uparrow\rangle_A \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_B \right) \otimes |\uparrow\rangle_N = \frac{1}{\sqrt{2}} \left( |\uparrow\rangle_A \otimes |\uparrow\rangle_N \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_N \otimes |\uparrow\rangle_B \right).
\]

This initial state overlaps with three out of eight eigenstates of the system, $\psi_2$, $\psi_3$, and $\psi_5$. At extremely low fields, two of these three states are degenerate. The third one is split from the other two by the hyperfine interaction, as shown in Fig. 1. Due to this, even in hypomagnetic conditions, this energy difference results in S-T mixing.

The probability of finding the radical pairs in singlet states starting from singlet states at some later time can be written as:

\[
\left\langle \hat{\rho}^S(t) \right\rangle = \text{Tr}[\hat{\rho}^S(t)] = \sum_{m=1}^{M} \sum_{n=1}^{M} \langle m | \hat{\rho}^S(t) | n \rangle \langle n | \hat{\rho}^S(t) | m \rangle,
\]

where the coherent evolution of the pair can be obtained using Eq. 11:

\[
\hat{\rho}(t) = e^{-i\hat{H}t} \hat{\rho}(0) e^{i\hat{H}t} = \frac{1}{M} e^{-i\delta t} \hat{\rho}^S e^{i\delta t},
\]

\[
\langle n | \hat{\rho}(t) | m \rangle = \hat{\rho}(t)_{nm} = \frac{1}{M} \langle n | e^{-i\delta t} | n \rangle \langle n | \hat{\rho}^S | m \rangle \langle m | e^{i\delta t} | m \rangle = \frac{1}{M} P^S_{nm} e^{i[\omega_n - \omega_m]t}.
\]

Combining Eq. 15 and Eq. 17,

\[
\left\langle \hat{\rho}^S \right\rangle(t) = \frac{1}{M} \sum_{m} \sum_{n} |\langle m | \hat{\rho}^S | n \rangle|^2 e^{i[\omega_n - \omega_m]t}.
\]

4/15
As $\langle \hat{P}^S \rangle (t)$ is necessarily a real quantity and assuming that the spin of the radical pairs start off from a singlet state, Eq. 18 can be rewritten as:

$$\langle \hat{P}^S \rangle (t) = \frac{1}{M} \sum_4^{4M} \sum_4^{4M} \left| \langle m | \hat{P}^S | n \rangle \right|^2 \cos (\omega_m - \omega_n) t.$$  \hfill (19)

The probability $\langle \hat{P}^S \rangle (t)$ depends on other contributions, including kinetic reactions, spin relaxation, vibration and rotation of radical pairs, which can be introduced in Eq. 19. Spin relaxation can be introduced phenomenologically \cite{32,33} such that:

$$\langle \hat{P}^S \rangle (t) \rightarrow \frac{1}{4} - \left[ \frac{1}{4} - \langle \hat{P}^S \rangle (t) \right] e^{-rt},$$  \hfill (20)

where $r$ denotes the spin relaxation rate. For the simple model here $\langle \hat{P}^S \rangle (t)$ as a function of time is presented in Fig. 2 for 1 $\mu$T and 50 $\mu$T with one isotropic hyperfine coupling of 1000 $\mu$T with $r = 10^6$ s$^{-1}$. The spin interaction on each unpaired electron on each radical, due to the combination of the hyperfine and Zeeman interactions, results in oscillation between the singlet and triplet yields. The fast oscillation is attributed to the hyperfine interaction, whereas the slow oscillation is caused by the Zeeman interaction, called quantum beat \cite{21,34,35}, where the beat note is related to the difference in energies between the two states that were previously degenerate (See Fig. 1). It is clear that quantum beat arises evidently in the presence of 50 $\mu$T compared to 1 $\mu$T. The general decay in both cases is because of the spin relaxation.

Following the work of Timmel et al. \cite{36}, the chemical fate of the radical pair can be modelled by separating spin-selective reactions of the singlet and triplet pairs. For simplicity, it is assumed that $k = k_S = k_T$, where $k_S$ and $k_T$ are the singlet and triplet reaction rates, respectively. The final singlet yield, $\Phi^{S(S)}$, for periods much greater than the radical pair lifetime reads as follows:

$$\Phi^{S(S)} = k \int_0^\infty \langle \hat{P}^S \rangle (t) e^{-kt} dt = \frac{1}{4} - \frac{k}{4(k+r)} + \frac{1}{M} \sum_4^{4M} \sum_4^{4M} \left| \langle m | \hat{P}^S | n \rangle \right|^2 \frac{k(k+r)}{(k+r)^2 + (\omega_m - \omega_n)^2},$$  \hfill (21)

where the fractional triplet yield can be calculated as $\Phi^{T(S)} = 1 - \Phi^{S(S)}$. Similarly, if the radical pairs start off in triplet states, the singlet yield fraction reads as follows:
Figure 2. $\langle \hat{P}^S \rangle(t)$ as a function of $t$. The probability of finding the radical pairs in singlet states starting from singlet states (Eq. 20) as a function of time with a hyperfine coupling constant of 1000 µT for external magnetic fields of 1 µT (Black) and 50 µT (Cyan) with a spin relaxation of $r = 10^6 s^{-1}$. In both cases, there is an interconversion of S-T due to the hyperfine interaction (fast oscillation); however, the slow oscillation (quantum beat) note only appears for the non-zero field and is related to the lifting of the degeneracy between the two upper states in Fig. 1.
Figure 3. Dependence of the fractional singlet yield on $B$. Dependence of the fractional singlet yield for (a) singlet-born ($\Phi^S$) radical pair on the external magnetic field $B$ with one isotropic hyperfine coupling of 1000 µT for different relaxation rate, $r$, and reaction rates, $k$. There is a peak in the hypomagnetic field range for most values of $k$ and $r$. The peak diminishes when the reaction rate is slower than the spin relaxation rate. One can also see that there is a dip at intermediate field values, then a rise at higher fields, but this rise is not as high as the peak for the hypomagnetic field range (see the inset).

\[
\Phi^S = \frac{1}{4} + \frac{k}{12(k+r)} - \frac{1}{3M} \sum_m \sum_n \left| \langle m | \hat{p}^S | n \rangle \right|^2 \frac{k(k+r)}{(k+r)^2 + (\omega_m - \omega_n)^2}.
\] (22)

Applied magnetic fields can alter the fractional singlet/triplet yield. Fig. 3 shows the dependence of the fractional singlet yield for singlet-born radical pairs for different sets of relaxation rate, $r$, reaction rate, $k$, and one isotropic hyperfine coupling constant. It is clear that there is a peak in the hypomagnetic field range for most values of $k$ and $r$. It is noteworthy that the peak diminishes when the reaction rate is slower than the spin relaxation rate. One can also see that there is a dip at intermediate field values, then a rise at higher fields, but this rise is not as high as the peak for the hypomagnetic field range. It should also be noted that the case of triplet-born and singlet-born radical pairs have the same behavior, but with peaks and dips exchanged.

2.2 Hypomagnetic field effect

One can define hypomagnetic field effects, $\Delta \Theta_{HMF \leftrightarrow GMF}$, as the absolute value of the ratio of the difference between the singlet (triplet) yield at near zero magnetic field (1 µT) and at the geomagnetic field range (50 µT) over the singlet yield at near-zero magnetic field:

\[
\Delta \Theta^{(j)}_{HMF \leftrightarrow GMF} = \left| \frac{\phi^{(j)}_{HMF} - \phi^{(j)}_{GMF}}{\phi^{(j)}_{HMF}} \right| \%.
\] (23)
Figure 4. Dependence of $\Delta \Theta_{HMF \leftrightarrow GMF}^{S(S)}$ on $a$, $r$, $k$. One of the radicals is coupled to a nucleus with $\frac{1}{2}$-spin and the other one with no hyperfine interaction. The hypomagnetic field effects are more evident when the hyperfine coupling is larger than the spin relaxation and reaction rates. This is even more pronounced when the spin relaxation is slower than the reaction rate. If the hyperfine coupling constant is much larger than the reaction and spin relaxation rate, the hypomagnetic field effects can reach considerable values (say $>10\%$) for $a < 20000 \mu T$ (e.g. Blue curve). $\gamma_e = 1.76 \times 10^{11} \text{s}^{-1} \text{T}^{-1}$ is the electron magnetogyric ratio. Due to the dominance of the hyperfine interaction over the Zeeman interaction, for too high values of the hyperfine coupling constant, there are no hypomagnetic field effects; this depends on the relaxation and reaction rates.

where $i, j = \{S,T\}$.

We numerically explore the hypomagnetic field effects for the radical pair model using Eq. 23. This is particularly relevant for experiments based on screening the geomagnetic field (of which there are quite many).

Fig. 4 shows the dependence of the hypomagnetic field effect on the hyperfine coupling constant for different sets of relaxation and reaction rates. It is worth noting that the hypomagnetic field effects are more evident when the hyperfine coupling is larger than the spin relaxation and reaction rates. This is even more pronounced when the spin relaxation is slower than the reaction rate. It is also worth mentioning that if the hyperfine coupling constant is much larger than the reaction and spin relaxation rate, the hypomagnetic field effects can reach considerable values (say $>10\%$) for $a < 20000 \mu T$. For too high values of the hyperfine coupling constant, there are no hypomagnetic field effects. This is due to the fact that, for all different rates, at far too large hyperfine couplings, the hyperfine interaction dominates the Zeeman interaction, and hence there are no quantum beats.

Fig. 5 shows the hypomagnetic field effects based on the singlet yield ratio with singlet initial states,
Φ^{S/(S)}$, where that one of the radicals is coupled to one nuclear spin-$\frac{1}{2}$ with a hyperfine coupling of 1000 µT. The effect is higher than 10% when $k \in [10^5 - 10^7] \text{ s}^{-1}$ and $r < 10^6 \text{ s}^{-1}$. The maximum value for hypomagnetic field effects for singlet-born radical pairs reaches $\sim 40\%$.

Most of the organic radicals possess several nuclei carrying spin with positive or negative isotropic hyperfine coupling constant. Fig. 6 shows the dependence of the hypomagnetic field effect on spin relaxation rate and reaction rate for these sets of isotropic hyperfine coupling constants: $a_{iso} = \{+500, +500\} \mu T$, $a_{iso} = \{+500, -500\} \mu T$, and $a_{eiso} = \sqrt{2500} \mu T$. The signs of the hyperfine couplings have a minor impact on the fractional yield for the hypomagnetic field effects. Here, one of the radicals is coupled to two nuclei, and there is no hyperfine interaction for the other radical. $a_{eiso}$ is the effective hyperfine coupling constant:

$$a_{eiso} = \sqrt{\frac{4}{3} \sum_i a_i^2 I_i (I_i + 1)}.$$ (24)

The effect is higher than 10% when $k \in [10^5 - 10^7] \text{ s}^{-1}$ and $r < 10^6 \text{ s}^{-1}$. In this range of parameters, the effective hyperfine coupling constant shows stronger effects relative to the other sets of couplings.

We also investigate how the initial state of the radical pairs (singlet or triplet) impacts the hypomagnetic field effects. Fig. 7 shows the hypomagnetic field effects based on singlet/triplet yield with singlet/triplet initial states. The effect is evident when $k \in [10^5 - 10^7] \text{ s}^{-1}$ and $r < 10^6 \text{ s}^{-1}$. However, the effect is more pronounced when it is based on singlet (triplet) yield with triplet (singlet) initial states, $\Phi^{S(T)}(\Phi^{T(S)})$, whereas the effect based on triplet yield with triplet initial states, $\Phi^{T(T)}$, is less than 10%.

### 3 Discussion

In the present work, we aimed to present the physics behind the hypomagnetic field effects. By eigensystem analysis, we showed the splitting between the eigenstates of the Hamiltonian which overlap with the initial state of the radical pair. In a near-zero magnetic field, the degeneracy of the states is higher, and this is the root of the hypomagnetic field effects. We also explored the dependence of the effect on various scenarios. There is a peak in the hypomagnetic field range, which diminishes when the reaction rate is slower than the spin relaxation rate. The hypomagnetic field effects are also more evident when the hyperfine coupling is larger than the spin relaxation and reaction rates. The effects exhibit negligible dependence on the signs of the hyperfine coupling constants, where the effective coupling constant has larger effect size relative to the individual hyperfine interactions for multi-nuclei interaction. We also explored the impact of the initial state of the radical pairs (singlet or triplet) on the hypomagnetic field effects. We concluded that the effect is more pronounced when it is based on singlet (triplet) yield with triplet (singlet) initial states.

It should be noted that the radical pair model considered in the present work is simplified, where the reaction rates for singlet and triplet yields and the spin relaxation for both radicals are assumed equal. More realistic models of the radical pairs may provide further insight into the underlying mechanism behind these phenomena, e.g., solving the master equation and considering the role of entanglement, dipolar, and exchange interactions in the models. Recently it has also been suggested that extending the radical pair mechanism to triads of radicals may help explain hypomagnetic field effects.

A considerable amount of evidence shows that shielding the geomagnetic field has direct biological consequences, which in some cases could be detrimental. This could also be pertinent for the quest for life on other planets with different magnetic fields, including Mars, which has zero magnetic field.

Studies suggest the Laschamp excursion—the most intense geomagnetic event occurring over the last 50 kyr, with a quasi-reversed polarity of the geomagnetic field—in combination with the Grand Solar Minima, initiated substantial changes in the concentration and circulation of the atmospheric ozone, increased
The hypomagnetic field effect is based on the singlet yield ratio of 1 µT (HMF) over 50 µT (GMF) with singlet initial states. In this model, one of the radicals has no hyperfine interaction, and the other one is coupled to one nucleus with an isotropic hyperfine coupling constant of $a = 1000\mu T$. The hypomagnetic field effects are significant when $r < 10^6s^{-1}$, $k \in [10^{4.5}, 10^{6.5}] s^{-1}$, and $k < r$. 

**Figure 5.** Dependence of $\Delta \Theta_{HMF \leftrightarrow GMF}^{S(S)}$ on $k$ and $r$. The hypomagnetic field effect is based on the singlet yield ratio of 1 µT (HMF) over 50 µT (GMF) with singlet initial states. In this model, one of the radicals has no hyperfine interaction, and the other one is coupled to one nucleus with an isotropic hyperfine coupling constant of $a = 1000\mu T$. The hypomagnetic field effects are significant when $r < 10^6s^{-1}$, $k \in [10^{4.5}, 10^{6.5}] s^{-1}$, and $k < r$. 
Figure 6. Comparing different signs for the hyperfine couplings in the case of multiple nuclei. Dependence of $\Delta \Theta_{\text{HMF} \leftrightarrow \text{GMF}}^{S(S)}$ on $k$, $r$, and signs of the hyperfine coupling constants. The hypomagnetic field effect is based on the singlet yield ratio of $1 \mu T$ (HMF) over $\mu T$ (GMF) with singlet initial states. In this model, one of the radicals has no hyperfine interaction and the other one is coupled to two nuclei with these isotropic hyperfine coupling constants: (a) $a_{iso} = \{+500, +500\} \mu T$, (b) $a_{iso} = \{+500, -500\} \mu T$, (c) $a_{eiso} = 500 \sqrt{2} \mu T$. The signs of the hyperfine couplings have a negligible impact on the fractional yield for the hypomagnetic field effects. The effective coupling constant has a stronger effect than the other sets of coupling constants.
Figure 7. Impact of initial state of the radical pairs (singlet or triplet) on the hypomagnetic field effects. The hypomagnetic field effect is based on the singlet yield ratio with singlet initial states (a), the triplet yield ratio with singlet initial states (b), the singlet yield ratio with triplet initial states (c), and the triplet yield ratio with triplet initial states (d). In this model, one of the radicals has no hyperfine interaction and the other one is coupled to an isotropic hyperfine coupling constant of $a_{eiso} = 1000\mu T$. The effect is evident when $k \in [10^5 - 10^7] \text{ s}^{-1}$ and $r < 10^6 \text{ s}^{-1}$. However, the effect is more pronounced when is based on singlet (triplet) yield with triplet (singlet) initial states, $\Phi^S(T)(\Phi^T(S))$. 
atmospheric ionisation and ultraviolet radiation levels, leading to global climate shifts that caused major environmental changes. They concluded the excursions of the geomagnetic field could be potentially harmful to life. In other words, they proposed an indirect impact of the geomagnetic field deprivation on the mass extinction indirectly via the atmosphere. However, the present work suggests that the deprivation of the geomagnetic field might also have direct effects on biological systems.

In conclusion, our results suggest that quantum effects may underlie the hypomagnetic field effects on biological systems, in a similar fashion to other weak magnetic field effects in biology, e.g., magnetoreception in animals. Lastly, we conclude that hypomagnetic field effects on biology are promising for testing the radical pair mechanism and quantum biology in general.

Data Availability
The generated datasets and computational analysis are available from the corresponding author on reasonable request.

Acknowledgment
This work was supported by the Natural Sciences and Engineering Research Council of Canada.

Author Contributions
H.Z. and C.S. conceived the project. H.Z. performed formal analysis, investigation, methodology, software, visualization with feedback from C.S.. H.Z. wrote the original draft with help from C.S. and R..

References
1. Zadeh-Haghighi, H. & Simon, C. Magnetic field effects in biology from the perspective of the radical pair mechanism. *J. The Royal Soc. Interface* 19, DOI: 10.1098/rsif.2022.0325 (2022).
2. Belyavskaya, N. Biological effects due to weak magnetic field on plants. *Adv. Space Res.* 34, 1566–1574, DOI: 10.1016/j.asr.2004.01.021 (2004).
3. Maffei, M. E. Magnetic field effects on plant growth, development, and evolution. *Front. Plant Sci.* 5, DOI: 10.3389/fpls.2014.00445 (2014).
4. Binhi, V. N. & Prato, F. S. Biological effects of the hypomagnetic field: An analytical review of experiments and theories. *PLOS ONE* 12, e0179340, DOI: 10.1371/journal.pone.0179340 (2017).
5. Zhang, B. & Tian, L. Reactive oxygen species: Potential regulatory molecules in response to hypomagnetic field exposure. *Bioelectromagnetics* 41, 573–580, DOI: 10.1002/bem.22299 (2020).
6. Zhang, Z., Xue, Y., Yang, J., Shang, P. & Yuan, X. Biological effects of hypomagnetic field: Ground-based data for space exploration. *Bioelectromagnetics* 42, 516–531, DOI: 10.1002/bem.22360 (2021).
7. Xue, X. *et al.* Biological effects of space hypomagnetic environment on circadian rhythm. *Front. Physiol.* 12, DOI: 10.3389/fphys.2021.643943 (2021).
8. da Silva, J. A. T. & Dobránszki, J. Magnetic fields: how is plant growth and development impacted? *Protoplasma* 253, 231–248, DOI: 10.1007/s00709-015-0820-7 (2015).
9. Tsetlin, V. *et al.* Effect of very small doses of ionizing radiation and hypomagnetic field change physiological characteristics of higher plant seeds. *Aerosp. Environ. Medicine* 50, 51–58, DOI: 10.21687/0233-528x-2016-50-6-51-58 (2016).
10. Raup, D. M. & Sepkoski, J. J. Periodicity of extinctions in the geologic past. *Proc. Natl. Acad. Sci.* **81**, 801–805, DOI: 10.1073/pnas.81.3.801 (1984).

11. Lipowski, A. & Lipowska, D. Long-term evolution of an ecosystem with spontaneous periodicity of mass extinctions. *Theory Biosci.* **125**, 67–77, DOI: 10.1016/j.thbio.2006.01.001 (2006).

12. Becker, R. O. Relationship of geomagnetic environment to human biology. *New York state journal medicine* **63**, 2215–2219 (1963).

13. Beischer, D. E. The null magnetic field as reference for the study of geomagnetic directional effects in animals and man. *Annals New York Acad. Sci.* **188**, 324–330, DOI: 10.1111/j.1749-6632.1971.tb13107.x (1971).

14. Beischer, D. E., Miller II, E. F. & Knepton, J. C. Exposure of man to low intensity magnetic fields in a coil system, vol. 1018 (Naval Aerospace Medical Institute, Naval Aviation Medical Center, 1967).

15. Dubrov, A. P. *The Geomagnetic Field and Life* (Springer US, 1978).

16. Alken, P. *et al.* International geomagnetic reference field: the thirteenth generation. *Earth, Planets Space* **73**, 49, DOI: 10.1186/s40623-020-01288-x (2021).

17. Fessenden, R. W. & Schuler, R. H. Electron spin resonance studies of transient alkyl radicals. *The J. Chem. Phys.* **39**, 2147–2195, DOI: 10.1063/1.1701415 (1963).

18. Sagdeev, R. Z. *et al.* Effects of magnetic field on chemical reactions. *Org. Magn. Reson.* **5**, 603–605, DOI: 10.1002/mrc.1270051212 (1973).

19. Brocklehurst, B. *et al.* The effect of a magnetic field on the singlet/triplet ratio in geminate ion recombination. *Chem. Phys. Lett.* **28**, 361–363, DOI: 10.1016/0009-2614(74)80366-0 (1974).

20. Hayashi, H. *Introduction to Dynamic Spin Chemistry* (WORLD SCIENTIFIC, 2004).

21. Steiner, U. E. & Ulrich, T. Magnetic field effects in chemical kinetics and related phenomena. *Chem. Rev.* **89**, 51–147, DOI: 10.1021/cr00091a003 (1989).

22. Xu, J. *et al.* Magnetic sensitivity of cryptochrome 4 from a migratory songbird. *Nature* **594**, 535–540, DOI: 10.1038/s41586-021-03618-9 (2021).

23. Smith, J., Zadeh-Haghighi, H., Salahub, D. & Simon, C. Radical pairs may play a role in xenon-induced general anesthesia. *Sci. Reports* **11**, DOI: 10.1038/s41598-021-85673-w (2021).

24. Zadeh-Haghighi, H. & Simon, C. Entangled radicals may explain lithium effects on hyperactivity. *Sci. Reports* **11**, DOI: 10.1038/s41598-021-91388-9 (2021).

25. Zadeh-Haghighi, H. & Simon, C. Radical pairs can explain magnetic field and lithium effects on the circadian clock. *Sci. Reports* **12**, 269, DOI: 10.1038/s41598-021-04334-0 (2022).

26. Rishabh, R., Zadeh-Haghighi, H., Salahub, D. & Simon, C. Radical pairs may explain reactive oxygen species-mediated effects of hypomagnetic field on neurogenesis. *PLOS Comput. Biol.* **18**, e1010198, DOI: 10.1371/journal.pcbi.1010198 (2022).

27. Zadeh-Haghighi, H. & Simon, C. Radical pairs may play a role in microtubule reorganization. *Sci. Reports* **12**, DOI: 10.1038/s41598-022-10068-4 (2022).

28. Sakurai, J. J. & Commins, E. D. Modern quantum mechanics, revised edition. *Am. J. Phys.* **63**, 93–95, DOI: 10.1119/1.17781 (1995).
29. Hogben, H. J., Efimova, O., Wagner-Rundell, N., Timmel, C. R. & Hore, P. Possible involvement of superoxide and dioxygen with cryptochrome in avian magnetoreception: Origin of zeeman resonances observed by in vivo EPR spectroscopy. *Chem. Phys. Lett.* **480**, 118–122, DOI: 10.1016/j.cplett.2009.08.051 (2009).

30. Player, T. C., Baxter, E. D. A., Allatt, S. & Hore, P. J. Amplification of weak magnetic field effects on oscillating reactions. *Sci. Reports* **11**, DOI: 10.1038/s41598-021-88871-8 (2021).

31. Schulten, K., Swenberg, C. E. & Weller, A. A biomagnetic sensory mechanism based on magnetic field modulated coherent electron spin motion. *Zeitschrift für Physikalische Chemie* **111**, 1–5, DOI: 10.1524/zpch.1978.111.1.001 (1978).

32. Bagryansky, V. A., Borovkov, V. I. & Molin, Y. N. Quantum beats in radical pairs. *Russ. Chem. Rev.* **76**, 493–506, DOI: 10.1070/rc2007v076n06abeh003715 (2007).

33. Hore, P. Upper bound on the biological effects of 50/60 hz magnetic fields mediated by radical pairs. *eLife* **8**, DOI: 10.7554/elife.44179 (2019).

34. Hore, P. J. Radical quantum oscillations. *Science* **374**, 1447–1448, DOI: 10.1126/science.abm9261 (2021).

35. Mims, D., Herpich, J., Lukzen, N. N., Steiner, U. E. & Lambert, C. Readout of spin quantum beats in a charge-separated radical pair by pump-push spectroscopy. *Science* **374**, 1470–1474, DOI: 10.1126/science.abl4254 (2021).

36. Timmel, C., Till, U., Brocklehurst, B., Mclauchlan, K. & Hore, P. Effects of weak magnetic fields on free radical recombination reactions. *Mol. Phys.* **95**, 71–89, DOI: 10.1080/00268979809483134 (1998).

37. Ramsay, J. & Kattnig, D. R. Radical triads, not pairs, may explain effects of hypomagnetic fields on neurogenesis, DOI: 10.48550/ARXIV.2206.08192 (2022).

38. McKay, D. S. *et al.* Search for past life on mars: Possible relic biogenic activity in martian meteorite ALH84001. *Science* **273**, 924–930, DOI: 10.1126/science.273.5277.924 (1996).

39. Hyodo, R. & Usui, T. Searching for life on mars and its moons. *Science* **373**, 742–742, DOI: 10.1126/science.abb1512 (2021).

40. Cooper, A. *et al.* A global environmental crisis 42, 000 years ago. *Science* **371**, 811–818, DOI: 10.1126/science.abb8677 (2021).