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# Magnetite in Human Tissues: A Mechanism for the Biological Effects of Weak ELF Magnetic Fields

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Due to the apparent lack of a biophysical mechanism, the question of whether weak, low-frequency magnetic fields are able to influence living organisms has long been one of the most controversial subjects in any field of science. However, two developments during the past decade have changed this perception dramatically, the first being the discovery that many organisms, including humans, biochemically precipitate the ferrimagnetic mineral magnetite ($Fe_3O_4$). In the magnetotactic bacteria, the geomagnetic response is based on either biogenic magnetite or greigite ($Fe_3S_4$), and reasonably good evidence exists that this is also the case in higher animals such as the honey bee. Second, the development of simple behavioral conditioning experiments for training honey bees to discriminate magnetic fields demonstrates conclusively that at least one terrestrial animal is capable of detecting earth-strength magnetic fields through a sensory process. In turn, the existence of this ability implies the presence of specialized receptors which interact at the cellular level with weak magnetic fields in a fashion exceeding thermal noise. A simple calculation shows that magnetosomes moving in response to earth-strength ELF fields are capable of opening trans-membrane ion channels, in a fashion similar to those predicted by ionic resonance models. Hence, the presence of trace levels of biogenic magnetite in virtually all human tissues examined suggests that similar biophysical processes may explain a variety of weak field ELF bioeffects. 

**Key words: greigite, honey bee, magnetosome**

## INTRODUCTION

### Magnetite Biomineralization in Animals

Most materials found in organisms are generally thought of as being non-magnetic—for example, either diamagnetic (repelled weakly from a magnetic field, as is water and almost any fatty substance) or paramagnetic (weakly attracted to a magnetic field, as is deoxyhemoglobin in blood cells). For materials of these types, the direct physical influence of the earth's magnetic field is extraordinarily weak,

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with the energy of magnetic interaction being many orders of magnitude below that of the background thermal energy, kT (where k is the Boltzmann constant and T the absolute temperature). However, another category of materials, termed ferromagnetic, interact very strongly with the earth's magnetic field. Unlike diamagnetic and paramagnetic substances, quantum-mechanical interactions acting on unpaired electrons within ferromagnetic materials force the electron magnetic moments (Bohr magnetons) to form long-range alignments. The magnetic moment from each Bohr magneton within such a crystal is added vectorially, and in some materials a crystal of only a few tens of nanometers in size will have magnetic interaction energies with the 50 microtesla (μT) geomagnetic field in excess of the background thermal energy. Motion of this material in response to external magnetic fields can in principle account for a variety of magnetic effects at the cellular level, such as the magnetic alignment of magnetotactic bacteria and algae [Frankel and Blakemore, 1980] or the magnetotactic response of honeybees [e.g., Kirschvink, 1981; Kirschvink and Kobayashi-Kirschvink, 1991; Kirschvink et al., 1992a]. As shown below, under some conditions the induced motions of magnetosomes can be large enough to open mechanically sensitive transmembrane ion channels, which in turn has the potential to influence a wide range of cellular processes.

At present, 12 iron minerals have been identified in organisms [Lowenstam and Weiner, 1989] although only two of these have been found so far as biochemical precipitates in vertebrates. These are ferrihydrite ($5Fe_2O_3 \bullet 9H_2O$), which is the mineral in the core of the ferritin molecule and the substance often referred to in the medical literature as hemosiderin, and magnetite ($Fe_3O_4$). Of these materials, ferrihydrite is paramagnetic while magnetite has a variety of ferromagnetism termed ferrimagnetism. Gram for gram, these properties make magnetite interact over $10^6$ times more strongly with external magnetic fields than does any other biological material.

The recent discovery that human tissues also contain trace amounts of magnetite (discussed below) also has profound biomedical implications. Magnetite is the first truly novel material to be discovered as a biochemical precipitate in human tissues since the dawn of medical science—everything else in human bones and soft tissue is either diamagnetic or paramagnetic (e.g., Lowenstam and Weiner, 1989). Magnetite is also the only known metallic compound to be made by living organisms and has the highest electrical conductivity of any cellular material. Although the total amount of magnetite in an adult human is small (a few hundred micrograms), there are several million crystals per gram, each of which interact rather strongly with external magnetic fields. As effects at the cellular level can often lead to global effects, particularly in the neurological and immune systems, it is important for human health to know what this material is doing in human tissues and how it forms.

Because magnetite is the only known biogenic mineral in higher organisms which is ferromagnetic at room temperature [Lowenstam, 1981; Lowenstam and Kirschvink, 1985], it is important to review briefly the history of its discovery in animals and what is known of its phyletic distribution and biological function. More extensive discussions of this subject are provided by Kirschvink [1989] and in the volume edited by Kirschvink, Jones, and MacFadden [1985].

Heinz A. Lowenstam [1962] of Caltech first discovered biochemically precipitated magnetite as a capping material in the radula (tongue plate) teeth of chi-

tons (marine mollusks of the class *Polyplacophora*). He and his students were able to demonstrate the biological origin of this material through a variety of radioisotope tracing studies and by detailed examination of the tooth ultrastructure [Towe and Lowenstam, 1967; Kirschvink and Lowenstam 1979; Nesson and Lowenstam, 1985]. Prior to this discovery, magnetite was thought to form only in igneous or metamorphic rocks under high temperatures and pressures. In the chitons, the magnetite serves to harden the tooth caps, enabling chitons to extract and eat endolithic algae from within the outer few millimeters of rock substrates. Nesson and Lowenstam [1985] report the results of detailed histological and ultrastructural examinations of magnetite formation within the radula and note that the process begins with an initial transport of metabolic iron to the posterior end of the radula sac. This iron is deposited as the mineral ferrihydrite within a pre-formed organic mesh of proteinaceous material [Towe and Lowenstam, 1967], forming one or two distinct rows of reddish teeth. Through an unknown process, this ferrihydrite is converted rapidly to magnetite through a non topotactic reaction, coupled with iron reduction and recrystallization.

Magnetotactic bacteria were the second organisms which were found to contain biogenic magnetite [Blakemore, 1975; Frankel et al., 1979]. They precipitate individual sub-micron sized magnetite crystals within an intracellular phospholipid membrane vacuole, forming structures termed "magnetosomes" [Gorby et al., 1988; Vali and Kirschvink, 1990]. Chains of these magnetosomes act as simple compass needles which passively torque the bacterial cells into alignment with the earth's magnetic field and allow them to seek the microaerophilic zone at the mud/water interface of most natural aqueous environments. These bacteria swim to the magnetic north in the northern hemisphere [Blakemore, 1975], to the magnetic south in the southern hemisphere [Kirschvink, 1980; Blakemore et al., 1980], and both ways on the geomagnetic equator [Frankel et al., 1981], although on the equator they have much lower population densities [Chang and Kirschvink, 1989]. Magnetite-bearing magnetosomes have also been found in a eukaryotic magnetotactic algae, with each cell containing several thousand crystals [Torres de Araujo et al., 1985]. The ferrimagnetic mineral greigite ($Fe_3S_4$)) has also been discovered in the magnetosomes of a primitive group of bacteria [Heywood et al., 1990; Mann et al., 1990].

Magnetite crystals formed within these magnetosome vessicles have three main features which serve to distinguish them from magnetites formed through geological processes. First, high-resolution TEM studies reveal that bacterial magnetites are nearly perfect crystals, usually elongate in the [111] direction [Mann et al., 1984a,b; Mann, 1985; Vali and Kirschvink, 1990]. Inorganic magnetites are usually small octahedral crystals, often with lattice dislocations and other crystal defects. The elongation of biogenic crystals in the [111] direction serves to maximize the net magnetic moment of the particle, and presumably is the result of natural selection for their magnetic properties [Kirschvink, 1989; Vali and Kirschvink, 1990; Kirschvink, 1992a]. Second, bacterial magnetite crystals are restricted to a size range from 30 to about 500 nm, with shapes which confine them to the single-domain magnetic stability field [Butler and Banerjee, 1975]. Inorganic magnetites tend to have log-normal size distributions, and range from super-paramagnetic to multi-domain in size. Third, bacterial magnetites tend to be rather pure iron oxide, with no detectable concentrations of the element titanium which is typically present in

geologically produced magnetite. These characteristic features have enabled bacterially precipitated magnetites to be identified in the fossil record in sediments up to 2 billion years old [Chang and Kirschvink, 1989].

As shown in Figure 1, these same features are shared by the magnetite crystals extracted from magnetotactic bacteria and salmon [Mann et al., 1988], and by some of those extracted recently from the soft tissues of the human brain [Kirschvink et al., 1992a]. Hence, the simplest interpretation of these results is that many higher organisms, including humans, possess the biochemical ability to form magnetite. This is hardly surprising in view of the wide phyletic distribution of magnetite-biomineralizing organisms [Lowenstam and Weiner, 1989].

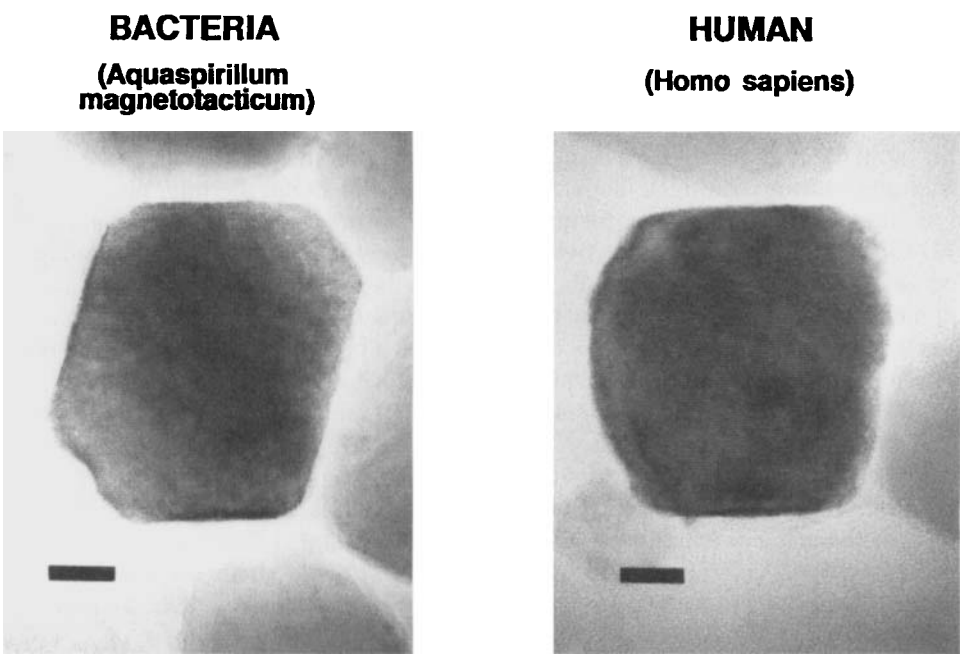


Fig. 1. Comparison of high-resolution (HR) TEM images of single-domain magnetite extracted from the magnetotactic bacterium, *Aquaspirillum magnetotacticum*, and from the human cerebellum. The scale bar is 10 nm in both images. The HRTEM image of the bacteria magnetite shows several sets of crystal lattice fringes (thin stripes) which correspond to three sets of {111} planes spaced a distance of 4.8 Å apart. In the human crystal, there is a pattern of two intersecting {111} and $\{11\bar{2}\}$ lattice fringes (4.8 Å and 2.9 Å, respectively), with particle elongation in the {111} lattice direction. Note the well-expressed {111} faces caping both ends of this particle; this is a common feature of magnetite crystals formed within lipid-bilayer membrane vacuoles, and is unknown from geological magnetites of this size. Unless there are magnetotactic bacteria living in the human brain, the presence of these crystals in human tissues suggests strongly that humans possess the biochemical ability to form magnetite. Because these crystals are permanent magnets with metallic conductivity, they are totally unlike anything else in human tissues. Another category of magnetite particles (not shown) range up to 0.6 μm size. Many of the human magnetites are oxidized variably during the long extraction process to the ferrimagnetic solid-solution end member, maghemite.

Our knowledge of the biological functions of magnetite are as yet incomplete. In the chiton teeth, it serves as a hardening agent—it is the hardest known biogenic material formed by an organism. In the microorganisms, magnetite is responsible for the magnetotactic response of bacteria [Frankel and Blakemore, 1980] and eukaryotic algae [Torres de Araujo et al., 1985]. Magnetite also seems to be involved in the ability of many animals to use the geomagnetic field as an orientational or navigational cue; the magnetosome chains in the salmon, which strongly resemble those in the bacteria and algae, could certainly be used for this purpose [Mann et al., 1988]. Recent behavioral work with honeybees, showing that north-seeking bees can be changed into south-seekers with a brief magnetic pulse, confirms that a ferromagnetic material like magnetite is indeed part of the honeybee magnetic sensory system [Kirschvink and Kobayashi-Kirschvink, 1991].

There is a problem with this simple list of functions, however. Magnetite is now known to form commonly in a variety of tissues for which a sensory function is rather unlikely—human and mouse tumors, for example. Furthermore, many of the magnetite crystals extracted from the human brain show features which may be dissolution effects—illustrated by the variation in electron density by the human crystal shown here in Figure 1, for example. Hence, we suspect that magnetite has as yet unknown roles in eukaryotic biochemistry, perhaps as a localized source of iron for activating iron-based enzymes. The high levels of magnetite in rapidly growing mouse tumors [Kirschvink et al., 1982] hints that it may have a role in cell division.

### Summary

Biogenic magnetite has been found in many organisms ranging from bacteria to higher vertebrates, including humans. It is also present in many tumor materials. Where it has been studied fully, it forms single-domain (permanently magnetic) crystals held within lipid-bilayer vacuoles termed magnetosomes, often strung together in linear chains. These structures are "biological bar magnets," with interaction energies with the geomagnetic field exceeding thermal noise (kT). Biogenic magnetite provides easy and well-understood mechanisms for the geomagnetic field to influence processes at the cellular level, and it may also be involved with other cellular functions, such as iron transport or storage.

## BIOPHYSICS OF MAGNETITE: CAN IT EXPLAIN ELF BIOEFFECT?

There is at present a growing controversy concerning whether weak, extremely low-frequency (ELF) magnetic fields are capable of producing adverse biological effects. A proliferating number of recent epidemiological studies suggest links between childhood leukemia and ELF magnetic exposure [e.g., Wertheimer and Leeper; 1987; Savitz et al., 1988a,b; London et al., 1991], as well as many others. However, there are scientists who believe that power frequency fields cannot cause biological effects other than well-known effects like electrical shock and burn. Adair [1991a,b] in particular has presented a series of simple but quantitative arguments which show that many mechanisms which have been proposed (e.g., ion cyclotron resonance) do not work. Adair's approach is clearly correct, as the fundamental constraints of

statistical mechanics and thermodynamics cannot and must not be ignored. For any viable mechanism, it must be possible to show through quantitative calculations that the magnetic effects stand out above background fluctuations produced by thermal noise. Even though biological systems excel at non-linear amplification, non-linear effects cannot short-circuit the laws of thermodynamics, or we would be able to build perpetual motion machines. Thermal noise amplified by any system is still thermal noise; however, processes which average over large numbers of independent "receptors" can boost the signal-to-noise ratio by the square root of the number. Situations of this sort are well known in the nervous system (e.g., hearing) and even in the operation of proton precession magnetometers.

Although Adair's approach is clearly correct, his analysis is incomplete as witnessed by experimental data which contradict his major conclusion. In particular, all sensory perception rests, at some point, on the nervous system receiving input from specialized receptor cells. If there were no magnetic effects at the cellular level, then it follows that no terrestrial animal could have a behavioral response to the geomagnetic field. Hence, the honey bee's highly reproducible ability to respond to the background geomagnetic field, and even to be trained to discriminate small anomalies in it (discussed by Towne & Gould [1985], Walker and Bitterman [1989a,b], Kirschvink and Kobayashi-Kirschvink [1991], and Kirschvink et al. [1992]) demonstrates that Adair's analyses are not complete. As there is good evidence that magnetite is the key element in the honey bee's ability to sense magnetic fields [Kirschvink and Kobayashi-Kirschvink, 1991], his flaw probably lies in his inappropriate consideration of magnetite; this shows clearly when he writes, "But $Fe_3O_4$ is found in few other cells" [Adair, 1991a] and "magnetite is not generally found in mammalian cells" [Adair, 1991b].

Adair is not alone in this omission, as most recent reviews of possible mechanisms for the biological effects of magnetic fields ignore magnetite or treat it in a very cursory fashion [e.g., Tenforde and Budinger, 1986; Villa et al., 1991]. As discussed extensively in a discussion and reply on the topic [Kirschvink, 1992b; Adair, 1992], the presence of biogenic magnetite provides a very good mechanism, well within the scope of both conventional physics and modern biology, for understanding the interaction of ELF fields at the cellular level. Although all of the past analyses of magnetite in higher animals have focused on its role in sensory transduction [Kirschvink, 1979; Kirschvink and Gould, 1981; Kirschvink and Walker, 1985; Kirschvink et al., 1992b; Yorke, 1979, 1981, 1985], very similar analyses can be adapted to the problem of other (non-sensory) ELF bioeffects. In particular Kirschvink et al. [1992b] have developed a simple biophysical model for understanding the response of a magnetite-based sensory organelle moving in a viscous fluid which makes quantitative predictions concerning the frequency vs. sensitivity relationships expected for magnetite-based magnetoreceptors. As outlined below and by Kirschvink [1992b], a similar, biologically plausible physical model of a magnetosome oscillating in a 60-Hz, earth-strength field shows that this is capable of exerting enough force on a mechanically sensitive ion channel to cause it to open or close. Depending upon where such a channel is located, and whether it is coupled to secondary messenger systems, this could influence the cell membrane, DNA synthesis, RNA transcription, calcium release, and virtually any ionically mediated cellular processes. A variety of frequency-dependent effects of magnetosome motion

are also possible, many of which could be mistaken for the ion resonance effects which Adair [1991a] has criticized properly.

## BIOPHYSICS OF MAGNETITE AND MECHANICALLY SENSITIVE ION CHANNELS

Many of the effects reported in biomagnetic experiments suggest that the magnetic field acts somehow to alter the electrical properties of biological membranes. One of several possible mechanisms for producing dramatic biological effects from mechanical motions within a cell is the opening and closing of mechanically sensitive trans-membrane ion channels. These structures operate essentially at the kT limit, and external input of mechanical energy of $\Delta E$ will change the probability of a channel being open or closed by a Boltzmann factor of $\exp(-\Delta E/kT)$. If coupled perfectly, a magnetosome with a magnetic/thermal energy ratio of 10 in the geomagnetic field could act to change the probability of a gate being closed by a factor of $\exp(-10)$ (e.g., the probability at any time of the gate being closed could shift from a value near .99999 to a value of 0.00005). The nucleus is particularly sensitive to the concentration of $Ca^{++}$, as it inhibits the polymerization of the protein tubulin into the spindle fibers which separate chromosomes during cell division [Lowenstam and Margulis, 1980]. Nondisjunction (abnormal or absent chromosome numbers) is common in malignant cells. $Ca^{++}$ also controls many phosphorylation cascades, which are chemical systems of very high "gain." Mechanically sensitive ionic channels are present in almost every organism and tissue, including bacteria, yeast, invertebrates, higher plants, and vertebrates, and are known from oocytes, epithelia, endothelial cells, skeletal muscles, smooth muscles, and neurons [Sokabe et al., 1991]. In higher organisms there is good evidence that they are linked to the cytoskeletal system through spectrin-like proteins, and their number densities can be many per square micrometer [Sachs, 1991]. Biophysical properties of such channels are understood fairly well, largely through their identification on the stereocilia of hair cells. Opening of a single $C^{++}$ channel for a few milliseconds can lead to the firing of an action potential, and the sensitivity of these structures is such that they can "hear" the Brownian motion of the ciliary bundles [Denk and Webb, 1989]. Howard and Hudspeth [1988] have made estimates of the single-channel gating force, the difference between the force exerted on the ionic gate when it is open and that when it is closed, which are in the range between 0.2 and 0.4 piconewton (pN). Similarly, they found the gating distance for these channels to be about 4 nm. Hence, it is worth asking what types of external magnetic fields would be required to move a magnetosome enough to open a mechanically sensitive ion channel.

There are two basic types of motions that external magnetic fields might produce on an intracellular magnetosome: a translational force on the particle produced by gradients in the field, and a rotational torque generated as a particle tries to line up like a compass with the applied field. It is easy to show that the translational force for a sub-micron magnetite particle is well below thermal noise in virtually all situations encountered by human; hence, we only need to worry about the rotational torques.

A simple model for the torque interaction is that of a magnetosome coupled to an ion channel, Figure 2 is a hypothetical sketch of one such configuration [adapted

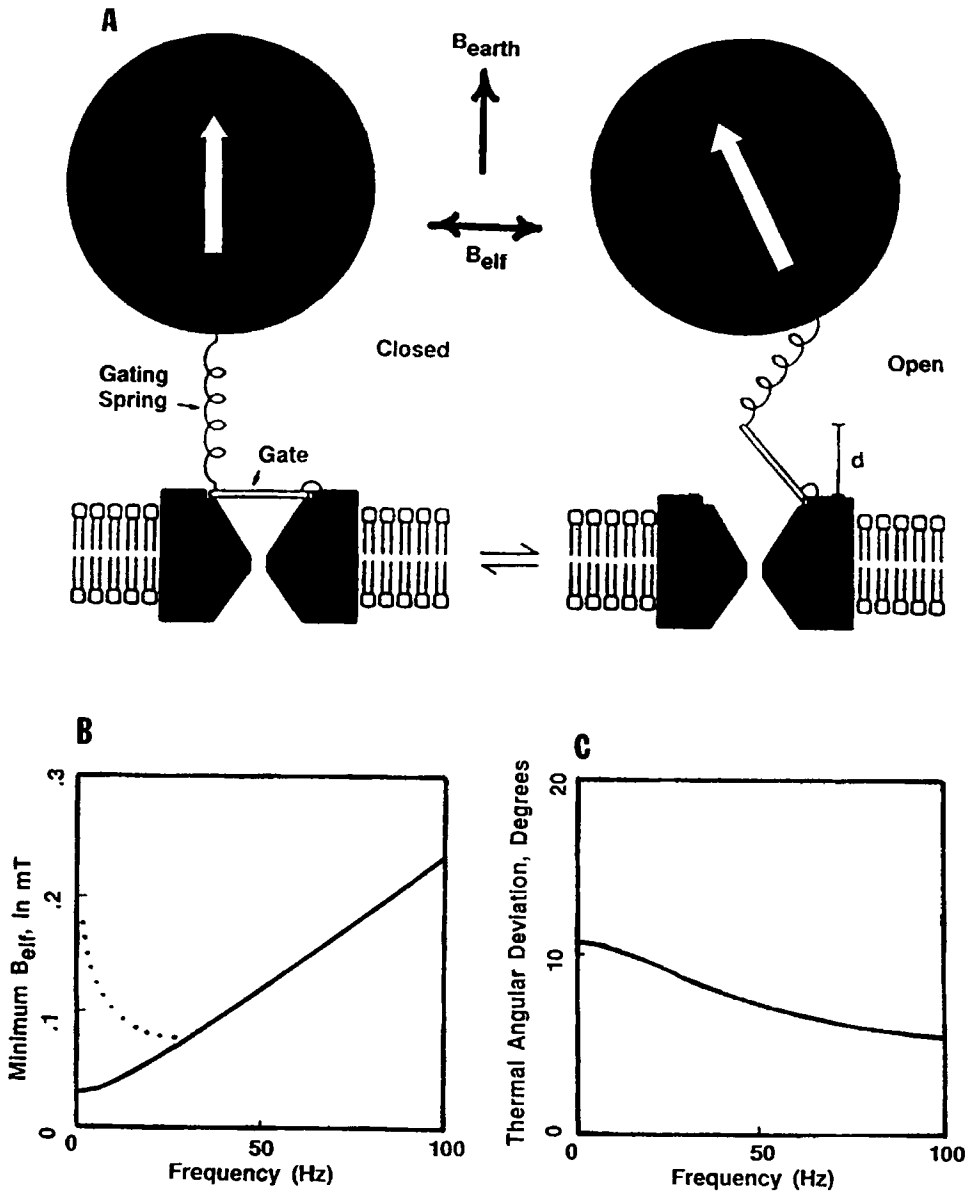


Fig. 2. A schematic diagram for how a magnetosome might act to open or close a mechanically sensitive trans-membrane ion channel, and order-of-magnitude estimates of the field levels required. **A:** A magnetosome connected to an ion channel gate via a cytoskeletal filament (a "gating spring"), adapted from Howard and Hudspeth [1988], but not drawn to scale as the magnetosome should be larger than shown. The geomagnetic field, $B_{earth}$, is perpendicular to the plane of the membrane, whereas the ELF component, $B_{elf}\cos(\omega t)$, is parallel to it. As discussed in the text, rotation of the magnetosome in response to the oscillating external field should be capable of opening and closing the ion gate. **B:** An order-of-magnitude estimate for the minimum fields to switch the gate as a function of frequency for a magnetosome of 0.1 μm radius in a fluid with a viscosity of 1 poise. The dotted line shows the approximate response change if membrane deformation is considered. **C:** The magnitude of the r.m.s. angular deviation produced by Brownian motion; this is below the 16° needed to open the gate. This

from Kirschvink, 1992b]. Assume that a cytoskeletal filament is anchoring the magnetosome to the membrane via a mechanically sensitive ion channel as shown. The background geomagnetic field, $B_{earth}$, of 50 μT is aligned perpendicular to the membrane, and we apply an ELF magnetic field, $B_{elf}\cos(\omega t)$, parallel to the membrane and perpendicular to $B_{earth}$. We wish to determine the minimum strength of the ELF magnetic field (as a function of frequency) necessary to open the ionic gate. To be conservative, assume that the gate opens through the distance, d, of 4 nm with an applied force, F, of 1 pN. To open the gate using a spherical magnetosome of radius, r, equal to 0.1 micrometer, this grain will need to rotate through an angle, $\theta_{min}$, of arcos (1 − d/r), or about 16 degrees. A magnetosome of this size and shape will be a single magnetic domain [Butler and Banerjee, 1975]. Magnetite crystals of this size have been extracted from the human brain and other organisms [Kirschvink et al., 1992; Kirschvink et al., 1985].

Under most circumstances, a magnetosome in a fluid medium will be overdamped critically by viscous forces (e.g., the low Reynolds number intracellular environment described by Purcell [1977]). Hence, inertial terms can be neglected, and the equation of motion is similar to that of a forced, overdamped torsional pendulum. In the situation shown in Figure 2, the torque on the magnetosome from the gating spring acts with the same $\sin(\theta)$ dependence as does the magnetic torque from the Earth's field. The equation of motion is then

$$c\theta + (Fr + \mu B_{earth})\sin(\theta) = \mu B_{elf}\cos(\theta)\cos(\omega t) \quad (1)$$

where C is the coefficient of rotational friction about the center of the magnetosome, $\theta$ is the angle between the static background field and the magnetic moment of the magnetosome, $\dot{\theta}$ is the angular velocity, μ is the total magnetic moment of the particle, $\omega$ is the frequency, and t is time. The magnetic moment for a magnetite particle of this radius is $2\times10^{-15}$ Am$^2$. For a sphere of this size, the coefficient of rotational friction is given by $6\eta V$, where V is the volume and $\eta$ is the viscosity of eukaryotic cellular protoplasm, which is about 100 times more than water [Keith and Snipes, 1974]. The stochastic rotations produced by Brownian motion are not included here, as they act independently of the other forces; for our purposes we note that the angular variance of motion, $<\theta_{therm}>^2$ is given by the thermal to magnetic energy ratio, $kT/\mu B_{total}$, and its RMS value should be less than the 16 degrees estimated above for opening the ionic channel gate.

Although equation 1 is a first-order equation, it does not have closed-form solutions for $\theta$ (t) due to the presence of the $\sin(\theta)$ and $\cos(\theta)$ terms. However, a close approximation to the correct solution can be found easily by the following approach. In the case where $\theta$ is small, $\sin(\theta)$ and $\cos(\theta)$ are approximately $\theta$ and 1, respectively. Equation 1 then becomes linear, and the solution for long times becomes

$$\theta(t) = \theta_{max}\cos(\omega t + E) \quad (2)$$

r.m.s. angular deviation decreases slightly with increasing frequency because the minimum value of $B_{elf}$, shown in B, increases. These calculations are made assuming that other cytoskeletal links prevent the magnetosome from drifting sideways while allowing it to rotate freely.

where

$$\theta_{max} = \frac{\mu B_{elf}}{\sqrt{(rF + \mu B_{earth})^2 + C^2 \omega^2}} \quad (3)$$

and E is the phase delay between the applied frequency and the response. Although this works for small $\theta$, if the value of $B_{elf}$ is much larger than $B_{earth}$, $\theta_{max}$ may become much larger than its maximum possible value $\pi/2$. In the low-frequency limit where $\omega$ approaches zero, $\theta_{max}$ should reduce simply to the arctangent of $B_{elf}/B_{earth}$. This modification also works for low values of $\theta$ because Arctan ($\theta$) is also $\theta$ in this limit. Hence, the function Arctan ($\theta_{max}$),with $\theta_{max}$ as given in equation 3 gives a close approximation to the maximum amplitude of the exact solution for equation 1 for all values of $\theta$. Numerical solutions for equation 1 confirm this to within a few percent.

Figure 2B shows the minimum values for $B_{elf}$ needed to make $\theta_{max}$ just equal to the 16 degree rotation for opening the ion gate as a function of frequency, and Figure 2C shows the expected angular deviation of the particle produced by Brownian motion, $<\theta>_{therm}$. At the powerline frequency of 60 Hz, the critical ELF field for opening the channel is 0.14 mT (1.4 gauss), and $<\theta>_{therm}$ is well below 16°. This estimate does not depend critically on the particle size chosen, as the viscous forces also decrease with the particle volume. For the smallest single-domain magnetite particle ~ 35 nm in diameter, we find a 0.5 mT field threshold. Note that the energy contributed to the ion channel goes roughly as the square of the field, hence doubling the field yields an effect of $e^4$ (~ 50) at the ion channel. Hence, slightly stronger fields (or elliptically polarized ELF fields) would tend to open the channels for longer periods.

Another matter of concern is the time constant for motion of the magnetosome, given by the ratio $6\eta V/\mu B_{earth}$ [Adair, 1992]. For any sized magnetosome in cytoplasm, this turns out to be about 25 ms, which is comparable to the 17 ms period of a 60 Hz sine wave.

This sketch is, of course, a simplistic model because nothing is yet known about the ultrastructural location of the non-sensory magnetite in vertebrate tissues. An obvious problem with the sketch as shown is that a 90° rotation of the magnetic field would cause the gate to open permanently. Humans move around in the magnetic field, and natural selection would have removed any harmful effect of such motion long ago. For this sketch model, two factors should act to mitigate this at very low frequencies. First, mechanically sensitive trans-membrane ion channels are phasic, closing on their own with an exponential time constant of about 0.1 seconds after sudden onset of a unidirectional membrane stress [Moody and Bosme, 1989]. Second, a small force on a biological membrane will cause it to deform, with a characteristic time constant also of about 0.1 seconds [Hochmuth and Waugh, 1987]. These effects may be related, as closure of the channels may be a result of membrane deformation relieving stress in the cytoskeleton. Hence, at frequencies below about 10 Hz there should be minimal effects of alternating fields of virtually any strength, as the ion channels and membranes have enough time to respond. At higher frequencies the membranes and channels should behave in the manner assumed in the model. Note that the net result is a maximum effect of ELF fields at

low frequencies, conditions in general similar to those proposed to support ionic resonance models.

In summary, the magnetite hypothesis provides a mechanistic basis for understanding some potential effects of weak, ELF magnetic fields and leads to testable predictions. In terms of risk assessment, this model already suggests that the fields generated by most electric transmission lines (c.a., 3 milligauss or 0.3 μT) are about 200 times below the thermal noise limit for a magnetite-based effect (unless an averaging process is involved). On the other hand, the stronger ELF fields produced by common household appliances (hair dryers, electric blankets, etc.) are often well above this limit and may be of more concern. Because humans do not typically spin themselves at 60 Hz in the geomagnetic field for extended periods of time, alternating fields of earth strength are not something which cells have been exposed to during most of the past 3.5 billion years of organic evolution.

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