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Influence of varying magnetic field on motion of Magnetotactic Bacteria

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***Abstract*— Magnetotactic bacteria are able to align their swimming direction to the geomagnetic field lines because they possess a magnetic moment. The dynamics of the magnetotactic bacterium in a varying magnetic field is investigated and analyzed by a theoretical model. The trajectory of the bacteria has been setup and the diffusion coefficient has been evaluated. The possibility to quantify the process of a reversal in direction of the motion of the bacterium under the influence of rotating magnetic field has been explored.**

***Indexed Terms*— Magnetotactic Bacteria, Varying Field, Reversal, Magnetosomes**

I. INTRODUCTION

Iron biominerals are formed by a broad host of organisms, in which they serve various functions. For example, iron oxides formed by organisms serve for strengthening of tissues [1] and hardening of teeth [2]. Iron bio-minerals are also associated with iron overload diseases and involved in intracellular iron storage and detoxification and sensing of magnetic fields [3,4] and crystals of magnetic iron minerals have been found even in the human brain [5,6].

Bacteria are one of the simplest organisms found in nature. They are distinguished from eukaryotes and superior organisms because their genetic material is not contained in a nucleus but is free in the cytoplasm. However, despite their relative simplicity, bacteria inhabit Earth for longer than many other organisms and constitute the most abundant type of cell on our planet [7]. Magnetotactic bacteria (MTB) are microorganisms that biomineralize magnetic nanoparticles inside their cytoplasm. These magnetic nanoparticles are involved by a lipidic membrane, and each "membrane + magnetic nanoparticle" set is known as magnetosome [8]. Magnetosomes are arranged in linear chains in the cytoplasm, conferring a magnetic moment to the bacterial body, being able to interact with the geomagnetic field to orient its navigational direction to the geomagnetic field lines. This response is known as magnetotaxis, resulting from the magnetic torque among the geomagnetic field and the magnetic moment of the magnetosome chain, and for that reason, MTB are described as "living compasses." MTB were discovered independently by Salvatore Bellini in 1963 and Richard Blakemore in 1975 [9]. The first to observe MTB was Salvatore Bellini, an Italian physician from Pavia, Italy. In 1958, physicians from Pavia were asked to analyze the quality of water for human consume. Bellini was part of the team that studied the water quality, and he observed in water samples some bacteria that consistently accumulate in one side of water drops. After trying different stimuli, he discovered that they were affected by magnets. He called that bacteria as magnetosensitive. The first published observation of MTB was done in 1975 by Richard Blakemore in Massachusetts, USA [10]. His discovery was accidental, because his goal was to isolate Spirochaeta plicatilis from marine marsh muds. During his observations, he noted microorganisms migrating to one end of the drop of the mud on the microscope slide, and discover that the presence of magnets altered their swimming direction. He called magnetotaxis as the tactic response to magnetic fields.

Since their discovery in the early seventies [11] magnetotactic bacteria have been intensively studied for more than 30 years. These bacteria assemble linear arrays of nanometer-scaled ferromagnetic particles called magnetosomes that are synthesized in the periplasmic space and internalized in the cytoplasm where chains of magnetosomes are stabilized by interaction with filaments analogous to eukaryotic cytoskeletal filaments [12-14]. In contrast to the magnetoception of animals, the bacteria contain magnetic mineral crystal that force the bacteria into alignment - even dead cells align, just like a compass needle. The sensitivity of magnetotactic bacteria to the Earth's magnetic field arises from the fact these bacteria precipitate chains of crystals of magnetic minerals within their cells; to date, all magnetotactic bacteria are reported to precipitate either magnetite (Fe_3O_4) [15] or greigite (Fe_3S_4) [16]. These crystals, and sometimes the chains of crystals, can be preserved in the geological record as magnetofossils. The oldest unambiguous magnetofossils come from the Cretaceous chalk beds of southern England, though less certain reports of magnetofossils extend to 1.9 billion years old Gunflint Chert [17,18]. There have also been claims of their existence on Mars based on the shape of magnetite particles within the Martian meteorite ALH84001, but these claims are highly contested [19,20].

Physically, the development of a magnetic crystal is governed by two factors: one, moving to align the magnetic force of the molecules in conjunction with the developing crystal, while the other reduces the magnetic force of the crystal, allowing an attachment of the molecule while experiencing an opposite magnetic force. In nature this causes the existence of a magnetic domain, surrounding the perimeter of the domain, with a thickness of approximately 150 nm of magnetite, within which the molecules gradually change orientation [21].

Magnetotactic bacteria produce their magnetic particles in chains. The magnetic dipole of the cell is therefore the sum of the dipoles of each BMP, which is then sufficient to passively orient the cell and overcome the casual thermal forces found in a water environment. In the presence of more than one chain, the inter-chain repulsive forces will push these structures to the edge of the cell, inducing turgor [22].

Magnetotactic bacterial cells have been used to determine south magnetic poles in meteorites and rocks containing fine-grained magnetic minerals and for the separation of cells after the introduction of magnetotactic bacterial cells into granulocytes and monocytes by phagocytosis. Magnetotactic bacterial magnetite crystals have been used in studies of magnetic domain analysis and in many commercial applications including: the immobilisation of enzymes; the formation of magnetic antibodies, and the quantification of IgG; the magnetic separation, diagnostics and detection of analytes [23-25], detection and removal of Escherichia coli cells with a fluorescein isothiocyanate conjugated monoclonal antibody, immobilized on magnetotactic bacterial magnetite particles and the introduction of genes into cells. Reported applications include immunobinding and receptor binding assays, magnetic cell separation and DNA extraction techniques [26,27]. Physiological studies have shown that MTB have potential to participate in the biogeochemical cycling of several important elements including iron, nitrogen [28], sulphur [29] and carbon [16] in natural environments.

Commercial uses of bacterial magnetosome particles have been suggested including the manufacture of magnetic tapes and printing inks, magnetic targeting of pharmaceuticals, cell separation and the application as contrast enhancement agents in magnetic resonance imaging and their usefulness for detection of microtumours has been demonstrated [30]. Recently, ultrafine-grained magnetite particles from a Martian meteorite, which resembled the magnetosome crystals of recent bacteria, have been cited as putative evidence for ancient extraterrestrial life. Moreover, bacterial magnetosome formation might serve as a model system for the biomineralization of magnetic minerals in other organisms, as similar crystals of ferromagnetic material, mainly magnetite, has been found in a wide range of higher organisms and even humans. Understanding the physical nature of interactions, which these nanomagnets are capable of inside the bacteria [31], is of paramount importance for envisaging any directed drug delivery applications using nanomagnets.

Important information about the motion of magnetotactic bacteria can be obtained from the study of their behavior in time-dependent magnetic fields. The U-shaped trajectories of bacteria resulting from switching the direction of the magnetic field have been used to measure their magnetic properties [32]. Rotating magnetic fields can be used to determine the critical frequency below which a rotation of single magnetic bacterium is synchronized with the field [33,34]. This allows measurement of the ratio of the magnetic moment of the bacterium to its rotational drag coefficient. The present paper is devoted to the study of the effect of varying magnetic fields on the trajectory of the bacterium. Section – 2 is devoted to the discussion of the physical characteristics. The theoretical model has been build up in Section – 3 and Section – 4 is devoted to discussion of results.

II. PHYSICAL CHARACTERSTICS

Two different processes of mineral formation by living beings have been recognized. One process of mineral formation is known as biologically induced mineralization (BIM), and is characterized by bulk extracellular and/or intercellular mineral formation, without the elaboration of organic matrices. It produces minerals having crystal habits similar to those produced by precipitation from inorganic solutions. BIM processes are less controlled than organic matrix-mediated mineralization, and looks like a primitive stage in the evolution of biogenic mineral formation. The other process is known as biologically controlled mineralization (BCM). In general, the organism constructs an organic mold into which the appropriate ions are actively introduced to crystallize a mineral. The mineral type, orientation of crystallographic axes, and microarchitectures are under genetic control [35]. Magnetotactic bacteria distinguish from other bacteria because they biomineralize, through BCM, magnetic nanoparticles of magnetite, or greigite. Magnetite is a very interesting iron oxide because it is magnetic and a good conductor. Its free charge density is similar to that of some metals [36]. It is also a hard mineral, being used by chitons for tooth hardening [37]. Several studies show that greigite has similar electrical [38] and hardening use [39] as magnetite. The magnetic properties of nanoparticles have a strong dependence on the size: very small particles have a magnetic moment nonstable in the body, changing randomly its orientation and producing a null average magnetic moment. Those particles are known as superparamagnetic. If the size increases, the anisotropic energy also increases and creates an energy barrier that maintains the magnetic moment in a fixed direction. In that case, the nanoparticles behave as stable magnets and are known as single domains [40]. Magnetosomes are in the size range of magnetic single domains. The magnetic flux lines created by the magnetosome in the chain can be observed using the magnetic electron holography technique [41], showing the flux lines entirely aligned to the chain as corresponds with a dipolar field created by a single magnetic moment. So, it is appropriate to say that the magnetosome chain behaves as a compass needle. The linear arrange of magnetosomes is not energetically stable, because after some number of magnetosomes the best configuration is a ring. To maintain the linear configuration, magnetosomes are attached to the cytoskeletal filaments [42]. The first analysis done in magnetosomes was energy-dispersive X-ray microanalysis (EDS or EDX), showing that they are composed mainly by iron and oxygen. To show that they are the iron oxide magnetite, the Mossbauer technique was used [43], showing that the Mossbauer spectra behave as a mixture of magnetite and maghemite. Also, electron diffraction shows the diffraction patterns corresponding to magnetite [44]. Several studies with EDS show that this magnetite is highly pure. However, in some cases, some metallic ions can be absorbed in the magnetosome structure, depending on the ambient pollution [45]. Studies done with high-resolution electron microscopy show that magnetosomes are produced in specific geometric morphologies [46]. Those morphologies are truncated cuboctahedron, elongated cuboctahedron, and hexagonal prisms. In the case of greigite, the crystalline morphologies are truncated cuboctahedrons and elongated rectangular prisms [46]. This iron sulfide was discovered in magnetosomes of multicellular magnetotactic prokaryotes, and identified through EDX spectroscopy and electron diffraction [47].

III. THERORETICAL MODEL

The simplest model that might be proposed for a magnetotactic bacterium is a rigid magnetic dipole $\vec{m}$ directed along *z*-axis in which the self-propelling motion of a bacterium occurs. The angular velocity of the bacterium $\vec{\Omega}$ is found from the viscous and magnetic torque balance, and the equation of the motion for its long axis reads

$$\begin{aligned} \frac{d\vec{z}}{dt} &= \vec{\Omega}\times\vec{z} \\ \varsigma\vec{\Omega} &= \vec{m}\times\vec{H} \end{aligned} \tag{1}$$

Here ς is the rotational drag coefficient of the bacterium. Applying eq. (1) to a field

$\vec{H} = H_o(\cos(kz - \omega t), \sin(kz - \omega t), 0)$ rotating in the *xy* plane with angular frequency ω, gives

$$\varsigma k \frac{d\vec{z}}{dt} = mH \sin(kz - \omega t)\,. \qquad (2)$$

Assuming that motion takes place in the plane of a rotating field, there is a phase lag of $\phi = kz - \omega t$ of the bacterium axis with the respect to the field direction is introduced and in this case the eq. (2) reduces to

$$\frac{d\phi}{dt} = \omega - \omega_c \sin\phi \qquad (3)$$

where $\omega_c = mH/\varsigma$ is the critical frequency below which synchronous motion of the bacterium and the field takes place. If $\omega < \omega_c$, eq. (3) has a steady solution with ϕ determined by $\sin\phi = \omega/\omega_c$. If $\omega > \omega_c$, eq. (3) has only a periodic solution

$$\phi = 2\tan^{-1}\left(\frac{\omega_c}{\omega} + \sqrt{1 - \left(\frac{\omega_c}{\omega}\right)^2} \tan\left(\sqrt{1 - \left(\frac{\omega_c}{\omega}\right)^2} \frac{\omega(t - t_o)}{2} \right) \right) \qquad (4)$$

Angular velocity of the bacterium is $\omega_c \sin\phi$. Since ϕ changes with time in the asynchronous regime, a characteristic back and forth motion of the magnetic dipole takes place. Corresponding to it there is change of orientation as illustrated in Fig. 1.

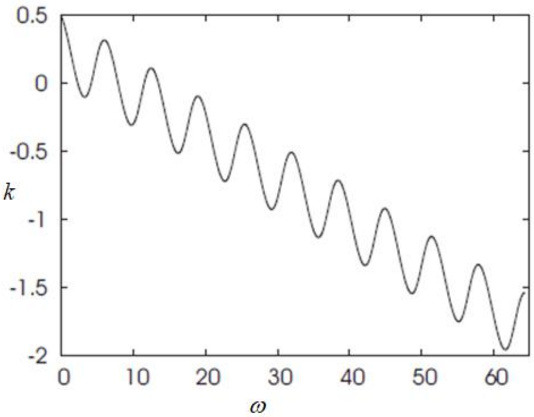

Fig. 1 : Back and forth motion of a bacterium along z-axis quantified by measurement of the angle between the bacterial axis and a reference direction for a period consisting of multiple rotations of the field ($\omega_c/\omega = 0.25$).

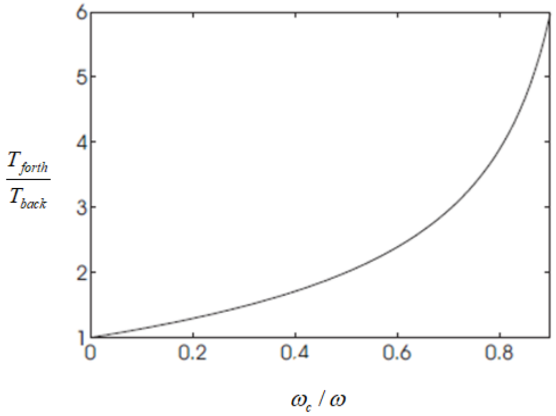

Fig. 2 : Ratio of times that the bacterium rotates forward T_{forth} and backward T_{back} as a function of the ratio of a critical rotation frequency and the field rotational frequency ω_c/ω .

The time interval during which the magnetic moment and the field rotate in the same direction is followed by a shorter time interval when the magnetic moment and the field rotate in opposite directions. The ratio of the time intervals for forward $(0 \le \phi \le \pi)$ and backward $(\pi \le \phi \le 2\pi)$ motion as a function of ω_c/ω calculated according to the relation $T_{forth}/T_{back} = (1+a)/(1-a)$, where $a = 2\tan^{-1}(\omega_c/\sqrt{\omega^2 - \omega_c^2})/\pi$ c is shown in Fig. 2.

CONCLUSION

Despite a quite long history of study of magnetotactic bacteria, their physical properties are not yet fully defined. Existing approaches mainly give qualitative information about their magnetic and hydrodynamic properties. In the present paper, it has been shown that studies of the motion of magnetotactic bacteria in rotating fields can provide rich information about their properties. It is even possible to determine the magnetic moment of a single bacterium by studying its thermal fluctuations in a rotating field. A rotating field also provides the possibility to quantify the process of a reversal in direction of the motion of a bacterium which has not yet been carried out. The physics of magnetotactic bacterium motion in a rotating field is rather rich and includes such phenomena as the escape of a bacterium in the third dimension out of the plane of a rotating field, a reversal-dependent diffusion process of the trajectory curvature centre, and other novel features. Their investigation is a challenge for the future experimental work.

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