Magnetotactic Bacteria and Their Significance for P Systems and Nanoactuators

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Summary. In the framework of the dialog between P systems and Microbiology, in this paper we focus on the magnetotactic behavior of magnetotactic bacteria, namely the orientation along the Earth's geomagnetic field lines. Magnetic properties and magnetotactic behavior could be used to obtained micro- and nanoactuators for the desired distribution at nanometer level of either intact magnetotactic bacteria or isolated intact magnetosomes with significant potential application in the construction of magnetic logic gates. Furthermore, (precise) distribution of intact magnetotactic bacteria or isolated intact magnetosomes by carefully using rather strong external magnetic fields could be described by P systems as a discontinuous process, whose potential for nanoactuators and magnetic microchips is increasing in evidence.

1 Introduction

The cell structure and function is one root of the emergence of P systems (Păun, 2000, 2001, 2002); moreover since the early days of P systems it become evident that its formalism has the potential to describe different biological processes occurring within the cell (Păun, 2002) and this trend is under increase with significant results (see Ciobanu et al., 2006; Hoogeboom et al., 2006, and references herein).

Here we focus on our proposal that magnetotactic bacteria could add some new insights into P systems, mainly with respect to the potential to use cell components for the construction of a P system-based computer.

In 1975 Robert Blakemore published his paper on magnetotactic bacteria (MTB). He stated that MTB's main functional characteristic is magnetotaxis, the orientation along the Earth's geomagnetic field lines (Blakemore, 1975). Magnetotaxis is determined by the presence inside the cell of particles named magnetosomes. These were originally defined as intracellular, magnetic single-domain (SD) crystals of a magnetic iron mineral (magnetite or greigite) that are enveloped by a

trilaminate structure, the magnetosome membrane. The discovery of MTB stimulated interest among microbiologists, physicists, engineers, geologists, chemists (Mann et al., 1990; Schüler and Frankel, 1999) and today the subject has become a *bona fide* field of research in microbiology (Bazylinski and Frankel, 2004). Probably it is the time for MTB to receive more attention from P systems, too.

Here we put forward that MTB or isolated magnetosomes are significant for membrane computing for the following reasons:

1. The synthesis of magnetite from iron salts is a complex process involving both plasma and magnetosome membranes (Schüler, 2002, 2004). Furthermore, isolated magnetosomes devoid of their membranes are no longer organized in an oriented chain; thus, the magnetosome membrane seems to be essential for the chain arrangement of magnetosomes both *in vivo* and *in vitro*, and this membrane has not been yet the subject of any P systems approach.
2. This process – not yet known in detail – could offer the possibility for P systems to develop quantitative discrete models for synergic biochemical and biophysical processes occurring at those biological membranes. This mathematical description could be further used for:
   a) to better understand the overall process of magnetosome formation and its regulation, by identification of still unknown functional proteins and/or regulatory components, by the use of different strategies developed within P systems; (i) metabolic P graphs (MPG) seems appropriate to identify new functional and regulatory components in different biological processes (Manca, 2006) not yet exploited with respect to MTB; (ii) as well as the proposed mesoscopic approach which is more tractable than the microscopic chemistry, but it provides a finer and better understanding than the macroscopic chemistry modeled by ordinary differential equations (Pérez-Jiménez et al., 2006);
   b) on line control of an *in vitro* reactor able to mimic the function of both plasma and magnetosome membranes in order to convert soluble nonmagnetic iron salts to magnetic nanocrystals.
3. MTB or isolated magnetosomes can contribute to the connection between P systems and the emerging domain of nanobiotechnology with special emphasis on the following:
   i) the construction of nanoobjects and their precise deposition/localization: MTB synthesize magnetic nanocrystals which can follow precise movements, orientations, and depositions by the use of either magnetotactic behavior of MTB or by (rather strong) external magnetic fields (see bellow);
   ii) to offer the opportunity to P systems to develop a software for discontinuous controlling and modelling of microdevices to be constructed (see below) for precise and oriented movement and deposition of MTB and their magnetosomes;

iii) to monitor the precise and oriented movement and deposition of MTB which transport at their cell surfaces different chemically linked molecules of functional significance, as for example immunoglobulins (see below).

4. Oriented MTB/magnetosomes chains could be used for the construction of magnetic logic gates. There are already experimental reports showing the increasing scientific interest in precise deposition of biotic magnetic crystals for the construction of magnetic logic gates able to execute logical NAND and NOR operations (Haque et al., 2004). These pioneering experimental results are directly related to the emerging filed of quantum dot magnetic computing from which there are expected huge effects on the speed of computation and on a new proposed generation of computers based on magnetism rather than electricity. We put forward that magnetic properties of single domain magnetic nanocrystals produced by MTB could be more appropriate than abiotic magnetic nanocrystals for the construction of magnetic logic gates and for the already proposed generation of computers based on magnetism rather than electricity. The properties of these magnetic computers could be further improved by the use of P system based software; this proposal is sustained by the already contribution from P systems to the field of quantum dot magnetic computing (Leporati et al., 2006; Leporati and Felloni, 2007).

2 Magnetotactic Bacteria

The morphology of single celled MTB is diverse (spirilla, vibrioids, cocci, rods to ovoid) and there are reports on multi- celled magnetotactic prokaryotes. MTB's main functional characteristic is magnetotaxis, the orientation along the Earth's geomagnetic field lines (Blakemore, 1975). Magnetotaxis is determined by the presence inside the cell of particles named magnetosomes (Frenkel and Blackmore, 1980; Frenkel et al., 1997)

Magnetosomes were originally defined as intracellular, magnetic single-domain (SD) crystals of a magnetic iron mineral that are enveloped by a trilaminate structure, the magnetosome membrane (MM). In other words, a magnetosome consists of magnetic iron mineral particles (the inorganic phase) enclosed within a membrane (the organic phase). In Figure 1 there is presented an original image of *M. gryphiswaldense* cell.

The organic phase (the magnetosome membrane or the magnetosome vesicle), consists in *Magentospirillum* strains (*M. magnetotacticum* or *M. gryphiswaldense*) of a bilayer of about 3-4 nm containing phospholipids and proteins. In the last few years the study of the proteins found in magnetosome membranes has raised a special interest because it was expected that these proteins would enable the processes of mineral formation of nanocrystals to be regulated by biochemical pathways (Schüler and Frankel, 1999; Bazylinski and Frankel, 2004).

The magnetosome particle is characterized by a nearly perfect crystallinity and the size and morphology of magnetic crystals are species specific and uniform

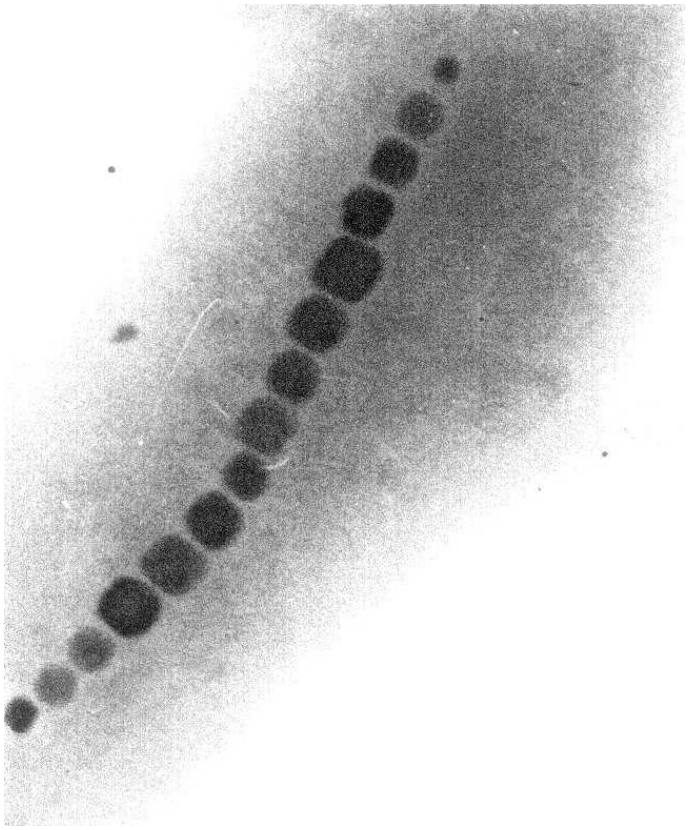

Fig. 1. Transmission electron microscope image of an intact cell of *Magnetospirilum gryphyswaldense*; one can see the chain of magnetosomes as dark bodies inside the bacterial cell (light grey).

within a single cell, for example, in *M. gryphiswaldense* the dimension of magnetosomes is around 45 nm (Schüler, 2004). This uniformity is an advantage of biogenic magnetic nanocrystals of MTB used for different bio(nano)technological application (Schüler and Frankel, 1999; Bazylinski and Frankel, 2004), as compared with biogenic magnetic nanocrystals produced by other types of bacteria or by artificial/abiogenic magnetic nanocrystals obtained by man using different physical/chemical protocols (Matsunaga, 1991; Schüler and Frankel, 1999). Biogenic magnetic nanocrystal can be produced by metabolic activities of dissimilatory iron-reducing bacteria and sulphate-reducing bacteria. This process is known as biologically induced mineralization. However, unlike the mineral particles in the magneto-tactic bacteria, biologically induced mineralization is not controlled by the organism and is characterized by no uniformity in size distributions and non-unique crystal habits.

We believe that the uniformity of biogenic magnetic nanocrystals of MTB can be further exploited for the construction of magnetic logic gates at nanometre level, with better results than the use of either abiotic magnetic nanocrystals or those produced by dissimilatory iron-reducing bacteria and sulphate-reducing bacteria.

It is still an enigma on how MM actually work in the process of controlled mineralization of iron during the process of magnetosome formation, but pioneering work had identified both at genetic and proteomic level the genes and magnetosome membrane proteins involved in magnetite formation. When the precise biological knowledge of the proteins/items involved in the magnetic nanocrystal formation will be achieved, it is expected that P systems could develop a model of this membrane processes, as it already started to carry out for other biological processes occurring at/within membranes: respiratory electron transport (Ardelean and Cavaliere, 2003; Ardelean et al., 2004; Cavaliere and Ardelean, 2006) the function of mechanosensitive channels (Ardelean et al., 2006) and many other processes (Ciobanu et al., 2006). medskip

Magnetotaxis. The passive orientation of MTB along the Earth's geomagnetic field lines is called magnetotaxis (Blakemore, 1975). Magnetotaxis is determined by the presence of magnetosomes. Dead cells containing magnetosomes also align along the geomagnetic field lines (around 0.05 mT), whereas alive MTB with no magnetosomes, do not align.

When magnetosomes are arranged in a single chain, as in the *Magnetospirillum* species, magnetostatic interactions between the single-magnetic domain particles cause the particle magnetic moments to spontaneously move parallel to each other along the chain direction. This results in a permanent magnetic dipole associated with the chain with a natural magnetization approaching the saturation magnetization and is sufficiently large enough to be oriented along the geomagnetic field at an ambient temperature (Frankel and Blakemore, 1980).

It is proposed that in natural environments magnetotaxis enables the cells to locate and maintain an optimal position in water columns or in sediments, with respect to their main metabolically needs: molecular oxygen and organic nutrients.

It is our hope that carefully deposition of MTB by the use of P systems-based models of magnetotactic behavior of intact cells during chemotaxis, and gently liberation of intact magnetosomes chains (retaining the surrounding membrane of each individual magnetosome particle) could be used for the construction of magnetic logic gates.

Magnetomanipulation of MTB. The orientation of MTB along the lines of magnetic field can be used to obtain in the lab surfaces covered by cells aligned with respect to the direction of the imposed magnetic field generated by two magnetic bars. This magnetomanipulation of magnetosome containing cells depends on their magnetotactic movement. In Figure 2 there are presented original images (optical microscope) concerning the experimental orientation of intact MTB on glass by the use of an external magnetic field; for the sake of simplicity the microscope images are accompanied by schematic drawings illustrating more clearly the orientation of MTB cells.

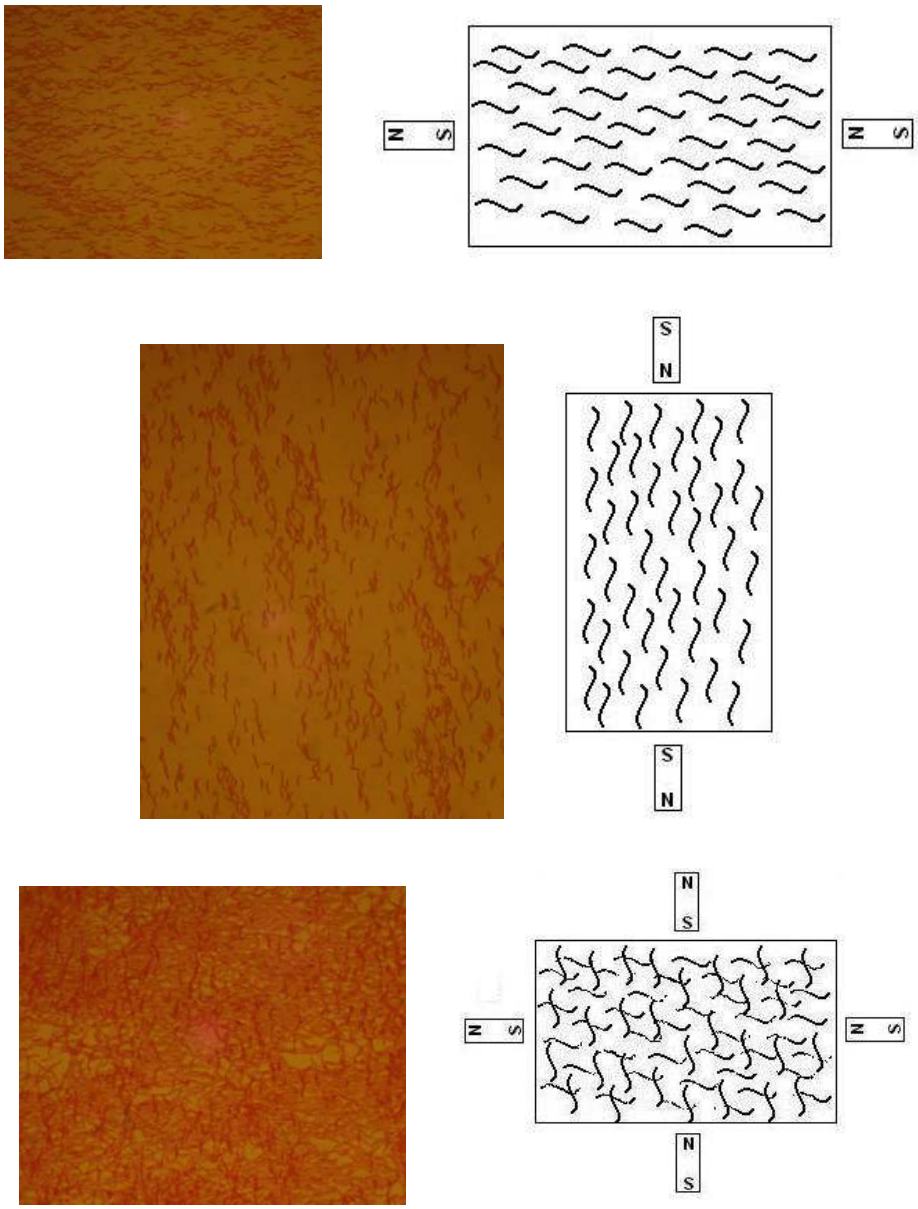

Fig. 2. The orientation of MTB along the lines of magnetic field; original optical microscope images (bright field, cells colored by basic fuxine) and schematic drawings: up = horizontal, center = vertical, and bottom = mixed (horizontal–vertical) orientation of MTB.

Controlled assembly of magnetic nanoparticles into ordered structures was demonstrated by manipulating magnetotactic bacteria in a fluid with microelectromagnets (Lee et al., 2004). The advantage of using magnetotactic bacteria cells is that the cellular bodies enclosing the magnetic chains prevent the magnetic aggregation of the bacteria, making it possible to use the bacteria as a carrier of ordered magnetic nanoparticles.

Microelectromagnets, consisting of multiple layers of lithographically patterned conductors, generate versatile magnetic fields on micrometer length scales, allowing sophisticated control of magnetotactic bacteria inside a microfluidic chamber (Lee et al., 2004). A single bacterium was stably trapped and its orientation was controlled; multiple groups of bacteria were assembled in a fluid. After positioning the bacteria, their cellular membranes were removed by cell lysis, leaving a chain and a ring of magnetic nanoparticles on a substrate. Thus, the authors demonstrated that the magnetic nanoparticles grown by the bacteria can be assembled into ordered structures. The new proposed approach, combining biomineralization and micromanipulation, can become a new method for growing and assembling nanoparticles into customized structures. Moreover, though integrated sensory means and new algorithms, the magnetotactic bacteria-based system could adapt or change the direction of motion from new occurring conditions (Lee et al., 2004).

It is our claim that a P system-based program could be more appropriate to model and control the direction of motion of these magnetotactic bacteria and to obtain ordered cells with magnetosomes useful for the construction of magnetic logic gates. The following picture suggests the use of a carefully designed (and constructed!) microdevice for true bacterial races!

The development of future autonomous bacterial microrobots (Martel, 2006) is another trend in which MTB can be involved. Acting like a compass, this chain of magnetosomes enables the bacteria to orient themselves and swim along the lines of a magnetic field. Hence, the basic control method consists of modifying the swimming paths of the MTB with the generation of local directional magnetic fields using small programmed electrical currents passing through special embedded conductor networks. This new method referred to as *controlled bacterial micro-actuation* is a serious candidate for its integration in future untethered microrobots operating in an aqueous medium, as originally proposed by the authors (Martel, 2006). The implementation of such bio-carriers with (non magnetic) micro-objects being propelled by a single MTB was also demonstrated. The effect of various diameters MTB-pushed beads on the velocity of this bio-carrier and the retarding effect caused by the proximity of the walls of the microchannels were also investigated. Thus by exploiting the motility of MTB, the electrical energy required to propel such a robot is null and the authors estimate that by pushing the limit of miniaturization or feature sizes to what is possible with actual microfabrication methods, a small current as low as 100 μA could be sufficient to control groups of pre-selected and most responsive MTB from a microcircuit embedded in the microrobot.

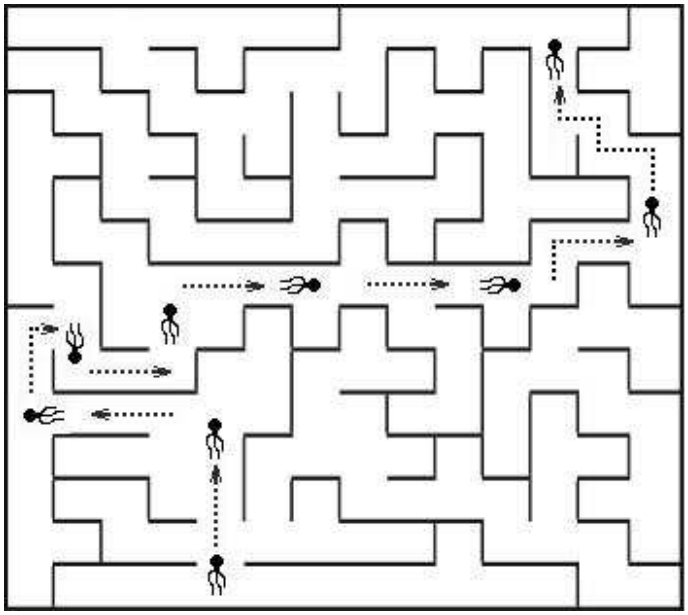

Fig. 3. Schematic picture of a microdevice for bacterial races (bacteriodrome?).

In our opinion such un-tethered microrobots could be used to transport biogenic magnetite produced by other bacterial cells, attached at their surface, and to release these nanocrystals at precise sites. Furthermore the concept of controlled bacterial micro-actuation (Martel, 2006) can be applied to obtain regular arrays of MTB which can be the basis for the construction of magnetic logic gates.

We have already designed a magneto-mechanical model of MTB with special emphasis on possible application in the field of nanoactuation (fore more details, see Ignat and Ardelean, 2004; Ignat et al. 2005, 2007). For example, the magnetosome chain microstructure can be moved and controlled with a 3 D system using magnetic levitation that represents an interesting microrobotic element.

The nanostructure of MTB suggests a nano- or micromanipulator structure which includes a flexible chain support with flexible joins and with magnetic elements which are small permanent magnets. These micromanipulator systems basically work within small magnetic gaps between the electromagnets (which generate the variable magnetic fields) and the motile chain. In Figure 4 there are presented some proposed structures for either flexible or rigid manipulators.

Our proposal to use magnetosomes, biogenic magnetic crystals covered by their biological membrane, as natural materials for the construction of magnetic logic gates and to construct nanoacutators based on either MTB or isolated intact magnetosomes could be helpful for the bottom up construction of a P systems-

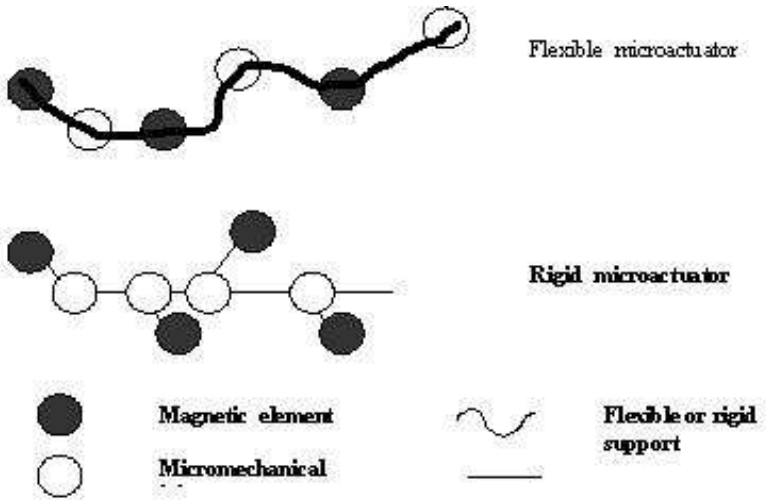

Fig. 4. Microarchitecture of nano or micro-magneto-manipulators.

based computer using natural components (biogenic magnetic nanocrystals) and P system-based software.

This proposal for the use of natural components for *in vitro* implementation of P systems and for the construction of a P system-based computer is in the line with the progresses made in the last four decades in incorporating different biological molecules into artificial membranes (Ottowa and Tien, 2002) which opened the way towards an *in vitro* implementation of P systems (see Ardelean, 2006, for more details).

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