Spatio-temporal pattern formation for the plasmodium of the true slime mould
— The network flow induces cellular behaviour —

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1. What is a true slime mould?

Under the five Kingdoms theory,[1] true slime moulds (真正粘菌, Myxomycetes 変形菌類) are Protoctista (原生生物界). The true slime mould sticks and lives on fallen leaves and rotten wood in the field after rain. When it turns fine, the true slime mould transforms itself into fruit bodies (子実体). They have intricate forms and various colours.[2]

Spores (胞子) are scattered from the fruit body by the wind. Under a suitable condition of germination, myxamoebae (粘菌アメーバ) come out from the spores. The myxamoeba multiplies by division. Two myxamoebae fuse to form a zygote (接合子), which multiplies by nuclear division and grows up to the plasmodium (変形体). The plasmodium repeatedly divides its nuclei but never divides its cytoplasm (細胞質), thus it grows up to a larger unicellular plasmodium. The matured plasmodium again forms the fruit body.[2]

Nuclei of the plasmodium simultaneously divide every 10 hours, and therefore it becomes a single giant cell with innumerable nuclei (coenocyte 多核単細胞). When the plasmodium is cut into small pieces, each piece behaves as an individual. If these pieces are put together, then they fuse to one organism.

Although the plasmodium has no brains or nerves, it can behaves in a coordinated way as an individual. Excellently rapid shuttle streaming is one reason of such behaviour. Its velocity exceeds 1 mm/s in maximal and changes the flowing direction every 100 seconds. This protoplasmic streaming transports chemicals and information everywhere in the cell.

2. Physiology of the plasmodial behaviuor

Physarum polycephalum (モジホコリ) is used in physiological researches because the method of its cultivation has been established. The plasmodium of *Physarum polycephalum* is cultivated on the agar medium with food of oat flakes.

The frontal expanding region of the plasmodium is a sheet-like fun, and protoplasmic veins appear in the rear part. The outer cortical layer of the plasmodium is ectoplasmic gel, and inner viscous fluid is endoplasmic sol. The sol-gel transformation of protoplasm is related to the shuttle streaming and network formation. The streaming flows nuclei, mitchondoria, and other organelle throughout the organism.

There is the fiber structure of actomyosin at the inner wall of the cortical gel tube, and fibers repeat the contraction-relaxation cycle every 100 seconds. This contraction cycle induces the endoplasmic streaming. Long fibrils run parallel along tubes of the plasmodium in the contraction phase, while a few short and slender fibrils appear in the relaxation phase.

The contraction-relaxation cycle goes with the various chemical substances.[3] Calcium ion (Ca^{2+}), adenosine triphosphate (ATP), and other metabolic chemicals oscillate with the same

frequency of contractile cycle. Results of various experiments indicate that metabolic oscillations regulate the contraction-relaxation cycle of fibrils.

The endoplasmic flow is passively induced by the pressure gradient, and its profile is similar to the plug flow in the structural viscous fluids.[4]

According to environments, the plasmodium changes its shape which is closely related to the contractile pattern.[5,6] For the roundly spreading plasmodium under the normal condition, the outer fringe is sheet-like structure and the inner region is consist of vein networks. The outer and inner regions oscillate with out of phase. The ultra-violet irradiation makes the plasmodium in vein-network form without the sheet-like structure, and travelling and rotating waves of contraction are observed. When the plasmodium forms the sheet-like structure and has no veins, the contractile wave travels with changes of its wave length and velocity.

The contractile pattern induces tactic behaviour (走性 taxis) of the plasmodium. For the attractive stimulation, the contractile rhythm becomes faster, and the phase gradient is formed on the plasmodium by the entrainment phenomena of oscillation. Then the contractile wave goes out from the stimulation point, and the plasmodium attracts to that point. In contrast, for the repulsive stimulation, the contractile frequency becomes slower, the wave goes into the stimulation point, and the plasmodium escapes from that point. There is some interesting experiment using the entrainment: if we control the temperature in slow oscillation, the plasmodium escapes from the warmer point, although the warmer condition is attractant for the plasmodium.[7]

There are various experiments on the formation of plasmodial tubes. Here, we comment one of them: the vein formation induced by contraction patterns.[6] In that experiment, the temperature of agar plate can be controlled independently in the left and right regions. After the plasmodium extends this agar plate, the temperature on both sides is varied sinusoidally with the same period, but the different phase. Then the contractile oscillation of the plasmodium becomes anti-phase between each sides, and veins are reinforced along the direction of the phase gradient of oscillation.

If we set the plasmodium some tasks, it responds by interesting behaviour. One of such tasks is a maze-solving problem.

After the plasmodium spreads and fills a maze, we put agar blocks containing nutrient (oat flakes) at the start and end points of the maze. Firstly, veins of the plasmodium reaching dead ends shrink. If there is enough nutrient, then the veins spanning long route become decay and a single thick vein finally spans a short route. Thus the plasmodium solves the maze (finds out the shortest route).[8]

Removing walls from the maze and putting more nutrient points on the agar, we set another shortest path problem called the Steiner problem (スタイナー問題). How does the plasmodium solve this problem? The answer of the plasmodium is not unique. Some plasmodia span the Steiner's tree completely or partially, but most plasmodia form mesh-like networks. Thus the plasmodium does not always select the shortest path and it often spans the redundant vein network to be robust and fault-tolerant.

3. Mathematical models

Mathematical models for the plasmodial behaviour are presented from the viewpoint of the information processing and pattern formation dynamics. Although these models are constructed

on various standpoints, we try to divide them into three classes and give a brief description of each model.

Coupled oscillators.[9,10] The system of coupled oscillators is well known for entrainment phenomena. The most simple element of this model is the phase oscillator, but other oscillators (amplitude oscillators, relaxation oscillators, ...) are often used and they are coupled in various ways. The main results of this model are that the frequency of oscillators are locked to the external oscillation, and the phase gradient is formed.

Reaction-diffusion-advection layers.[11] The metabolic dynamics of chemicals is described by reaction-diffusion equations with flow. The metabolic oscillators are in the gel layer and regulate the contractile stress of veins. The endoplasmic flow induced by this stress transports the metabolic chemicals. The phase wave, travelling wave and phase gaps appear in this system.

Active visco-elastic tube/sheet.[12,13,14] The continuity of mass describes the cytoplasmic transportation through the active visco-elastic tube. The interaction of some chemical substance and actomyosin causes self-excited oscillation of the tube. Although there are various visco-elastic models, the simple two-dimensional sheet in which a spring, a dashpot and an oscillator are connected in parallel is presented by Teplov and his collaborators. Quasi-static waves appear in this model.

As described above, the mathematical model for the plasmodial dynamics of cell shape is constructed from the stress generation based on the metabolic oscillation or contractile oscillation regulated by the metabolism (coupled oscillators), and mass transportation induced by the stress gradient (continuity of mass). However, to emerge the network formation dynamics, the model may need more modifications such as the conversion of substances (sol-gel transportation) and migration mechanism of the cellular boundary.

Until now, there are few experimental and theoretical studies on the dynamics of network formation. One difficulty of observations is to measure microscopic phenomena of the endoplasmic streaming allover the plasmodium. For the theoretical approach, it is a problem how networks are characterized. There are few studies on the transportation phenomena of nuclei, mitochondria (they are crucial parts of the genetic information and energy production, respectively) and other organelle. These intracellular organelle are passively transported by the endoplasmic flow.

4. Divergent epilogue

When we consider the plasmodial behaviour and construct a mathematical model, similar behaviour of other organisms may give a clue to understanding of the plasmodial motility. In the following, we comment on such organisms and their behaviour.

Bacteria (*Bacillus subtilis*). In colonies of bacteria which repeat multiplication and dormant, the branching morphology of spreading fronts depends on the agar concentration and nutrient concentration in the culture substrate. The branching front is similar morphology of the plasmodial front in some conditions. The colonial dynamics is described by the substrate-depleted system.[15]

Cellular slime moulds — another slime mould (*Dictyostelium discoideum*). Myxamoebae of a cellular slime mould aggregate by lack of nutrients and form a slug-like pseudoplasmodium, which finally develops a fruit body. In the aggregating stage, myxamoebae form spiral waves (like chemical waves of Belousov-Zhabotinsky reaction media), and then develop cell streams.[16]

This cell stream morphology resembles the contracting vein-network of the true slime mould in the rear.

Slime nets — yet another slime (*Labyrinthula*).   Colonies of net slime moulds are ectoplasmic networks spanning on algae. Net slimes move on slimy networks at the order of μm/s. The slimy networks are morphologically similar to the slime tracks of the plasmodium.

Army ants (*Eciton*).   Army ants form two types of raids by species, column raids and swarm raids.[17] In the column raid of *Eciton hamatum*, the advancing front is made up of small groups of workers and their trails develop to dendritic form. In the swarm raid of *Eciton burchelli*, the advancing front is made up of a large mass of workers and fan columns converge to base column. Both types of raids are exactly similar to expanding front of the plasmodium.

Cellular or collective behaviour of these organisms is expected to be based on quite common motile feature and mechanism.

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