Convection Pattern Formed by Photosensitive Microorganisms

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Euglena is one of the photosensitive microorganisms. It has been known that culture of Euglena forms macroscopic convection pattern, which is called "bioconvection," with strong light illumination from the bottom. In this presentation, I would like to introduce to the bioconvection pattern of Euglena and to show how to control it.

光応答性微生物が形成する対流パターン

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走性を示す微生物の多くは、一定の条件を満たすと巨視的な対流パターンを形成する（生物対流）。ミドリムシは走光性を示す単細胞の鞭毛虫である。このミドリムシの培養液を下から均一な光で照射すると、微生物が走光性により上に向かって泳ぐために、密度不安定な状態が形成され、対流パターンが形成される。ミドリムシの生物対流パターンは、容器の一部に局在化するという特徴がある。このため、培養液全体の平均の細胞密度に依存せず、局所的に細胞密度の高い領域が形成され、対流パターンが形成される。
ミドリムシの生物対流パターンの構造や特性波長を制御するために、培養液の深さや照射光の強度を変えたり、光マスクを利用したりした。照射光強度を 3000 lx に固定した時、深さが 3 mm 以下の時には斑点状にミドリムシの高密度領域が形成され、この斑点が３回対称性を持つ配置に等間隔に形成された。ところが、深さが 3 mm を超えると、パターンは転移して、線上の高濃度領域が迷路のように入り組んだ構造が形成された。また、深さを固定すると、光強度の増加に伴い、特性波長が短くなった。さらに、4 回対称性を持つ暗い斑点パターンのマスクを用いて光照射したところ、マスクのパターンの空間周期が生物対流パターンの周期に近いとき、マスクの構造を反映した 4 回対称性を持つ対流パターンが観察された。本講演ではこれらの観察結果をもとに、外部環境による生物対流パターンの制御について報告する。

Self-organization of microbial communities designed by dose-responserelationships

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We report microbial (Bacillus subtilis) self-organization embodying a growth and survival strategy against environmental perturbation, and present a prediction model for the macroscopic spatio-temporal dynamics.
We also show that the strategic self-organization is designed by dose-response correlations between environment and microbial activities.

用量反応関係が設計する微生物集団の自己組織化

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環境変動に対する成長生存戦略を体現する微生物（枯草菌）集団の自己組織化を報告し、その時空間動態の予測モデルを提案する。
また、この戦略的自己組織化が、環境と微生物活動の間の用量反応相関によって設計されていることを示す。

Collective motion of self-propelled particles with memory of rotation rate

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Some kinds of self-propelled particles, such as mycoplasmas, keep their rotation rate for a while. Using agent-based models and dynein-microtubule motility assays, we investigated the dependence of the collective motion of self-propelled particles on the correlation time of rotation rate. As a result, we found various phases caused by the finite
correlation time of rotation rate, such as vortex lattice, soliton phase, and so on.

回転速度を維持する自走粒子の集団運動

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マイコプラズマなどしばらく回転速度を維持する自走粒子が知られている。我々は自走粒子のエージェント・ベース・モデルとダイニン-
微小管の運動アッセイを用いて、回転速度の維持時間に対する集団運動の依存性を調べた。その結果、回転速度が有限時間維持される事によって渦の格子、ソリトン状の構造などが生じることを発見した。それらの詳細について発表する。

マガンの群れの集団動力学

Collective dynamics of skeins of geese and its stability

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In nature, animals often exhibit varieties of collective behavior in group, such as herds of quadrupeds, flocks of birds, and schools of fishes, which can be considered as an effective strategy to adopt the environment they live. Although such behavior is highly complicated and unsteady in general, under some appropriate space and time scales, one may expect that the dynamical behavior of individuals in a group and/or the motion of whole group can be understood in terms of some mathematical formulae with social interactions among members. Aiming to describe such collective dynamics of animals from the physical or mathematical point of view, we have studied the coordinated flight of wild geese in the northern region of the main island of Japan.

It is believed that large-size birds such as geese can reduce the energy required for flight by taking advantage of the upwash component of trailing vortices created from the leaders' wings. As a result, during their flight, they tend to merge forming a characteristic one-dimensional structure, which is often referred as skeins. On the other hand, skeins of geese may break into two or more sub groups due to destabilizing factors. In appropriate conditions under which large populations of geese exhibit dynamical rearrangements by repeated mergers and splits among the groups, we found that the distribution function in group size s is represented as $f(s) = As^{a-1}\exp(-bs)$, where $a = 0.58, b = 0.041$. Based on observations, we propose a mean-field model for the group-forming processes of geese in terms of the Smoluchowski equation of coagulation with fragmentation and plausible kernels. We derived the asymptotic form of the steady-state solution giving a good agreement with the group-size distribution as above. Furthermore, we estimated the effective number density of geese by comparing the model with field data [1]. Our study suggests that biological information processing like brain functions seems to be irrelevant to the adjustment of group size, at least, in the case of geese where large populations are involved.

When the size of skeins becomes large, even a single linear formation in skeins is not simply static but dynamic in space and time, and we can observe positional fluctuations propagating unidirectionally from front to back through skeins [2]. One may expect that such dynamical behavior originates from the excitation of the collective mode which intrinsically resides in the interacting many body system. Quantitative estimation of *effective* interactions, such as the magnitude of force, interaction range, response time, etc., would be the keys to understand this. Although one could hardly measure the force actually acting to flying birds, from their trajectories, we might be able to estimate how individuals in a skin regulate their position and velocity. In line with this idea, we developed a portable stereo camera system designed for field measurements for trajectory of individual birds in flocks.

Using the stereo camera system, we analyzed the time-dependent mutual positions between neighbors as well as response time of followers to leaders. We also scrutinized occasional events in which an outside goose joined in a skein of geese to become a member of the skein or a member suddenly broke away from a skein. We found that only the trailing individuals changed their position to readjust the formation during such process, while individuals in front of the joining or escaping goose did not. This indicates that interactions are asymmetric; leading birds are affected less by the actions of the followers than the other way around. Furthermore, spatiotemporal analysis suggests that the trailing individuals loosely synchronize their wing beat in the way that the flapping oscillation of nearest neighbors tends to becomes in-phase at the same position in the flight direction, in a similar way as the navigation of flight of hooded gulls [3]. Based on the obtained field measurements, we proposed a phenomenological equation of motion for the collective flight of geese and discussed the conditions for the stability of a collective flight.

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Equation-free analysis of collective behavior in particle models

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The coarse behavior and its parameter dependence in complex systems is investigated. For this, a numerical multiscale approach called equation-free analysis is discussed. The method allows to perform numerical investigations of the macroscopic behavior of microscopically defined complex systems including continuation and bifurcation analysis on the coarse or macroscopic level where no explicit equations are available. This approach fills a gap in the analysis of many complex real-world applications including particle models with intermediate number of particles where the microscopic system is too large for direct investigations of the full system and too small to justify large-particle limits. An implicit equation-free method is presented which reduces numerical errors of the analysis considerably. It can be shown in the framework of slow-fast dynamical systems, that the implicitly defined coarse-level time stepper converges to the true dynamics on the slow manifold. The method is demonstrated with applications to particle models of traffic as well as pedestrian flow situations. The results include an equation-free continuation of traveling wave solutions, identification of saddle-node and Hopf-bifurcations as well as two-parameter continuations of bifurcation points.

Dynamics of fish schools: rapid and slow time scales

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From the view point of time scale, we investigate dynamics of fish schools by analyzing the moving images filmed from the bottom of a tank of an aquarium. We focus on torus state of sardine schools among several ones of group, i.e. swarm, torus and parallel states.

In this talk, we discuss quite different time scales of dynamics of fish schools. one is related to their swift responce to predation, which are known as two activities, burst and agitation. Thier propagation speed are from 10 to 100 times faster than the usual swimming speed of individual fish.

Another time scale is dynamical time, within which fishes in torus have single rotation around center. In this time scale, we can observe collective motion of fish schools, which have universal natures.

Dynamics of fish schools: rapid and slow time scales

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水族館の底に設置したカメラで撮影した魚群の動画をの析結果を魚群のダイナミクスについて時間スケールに焦点をあてて報告する．
イワシ群れのさまざまな状態の中で，長時間の動的進化の議論にも適しているトーラス状態に注目する．

魚群は大きく異なる２つの時間スケールをもっている．ひとつは非常に速い時間スケールである．これは捕食者に襲われたときに魚群が見せる俊敏な反応に関係している．
短時間しか継続しないが通常の遊泳速度の１０倍程度で泳ぐバースト，さらにバーストのトリガーや回避行動のための方向転換が通常の遊泳速度の１００倍で伝搬するアジテーションなどに関連した時間スケールである．本講演ではこれらの過程の観測結果について紹介する．

一方，魚群は非常にゆっくりではあるがゆらぎの大きい非平衡進化をする．
個々の魚がトーラスを一回転する時間いわゆる動的時間が典型的な時間スケールである．
この動的時間スケールで観測される群の集団運動や普遍的性質についても議論する．

Collective effect in motile cyanobacteria

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A group of cells interact to form a macro structure accompanied by biological functions during morphogenesis. In this study, collective cell movement of motile cyanobacteria, *Pseudanabaeba*, sp., was investigated. The bacteria chained in a line glide on agar medium surface. We found that the collective bodies show a variety of colony patterns and movements: Single strands, bundles, and comet-like colonies show translational movements: Disk shaped colonies show rotating movement. Additionally, transitions among the patterns were observed. Combined with the analysis by a self-propelled particle model, we found that not only cell-cell interactions but also cell-environment interactions are key factors for the dynamical pattern formation. Further the biological functions of the colony morphologies will be discussed.

運動性シアノバクテリアの集団効果

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生物では、個体間の相互作用を通して集団秩序を形成し、生物機能を創発する例が至るところで見られる。本研究では、実験室レベルで観察可能な運動性シアノバクテリア *Pseudanabaena*, sp. を用いて、運動性個体の集団化の効果について調べた。このバクテリアは細胞が鎖状に連なった形態をしており、寒天培地に播種するとその表面上を滑走運動する。鎖状の個体が集団化した結果、多様な形態の運動性コロニーを形成することを我々は見出した。コロニー形態には、並進運動する束状または彗星状のものと、回転運動する円盤状のものがあり、その形態間を自発的に遷移する。速度解析により、単体よりも集団の規模が大きいほど運動速度が大きくなることが確かめられた。染色解析によりこのバクテリアは、多糖類を含む粘液を分泌することで、細胞と細胞、細胞と寒天培地の間で相互作用し、それが集団パターンに寄与する可能性が示唆された。この現象のメカニズムを理解するために、個体間相互作用と個体と環境の間の相互作用を仮定した自己駆動粒子モデルを構築し、解析を行った。その結果、二つの相互作用が多様な運動性集団形成に対する重要な制御パラメータであり、これによって、実験結果を現象論的に説明できることがわかった。これら結果からコロニー形態の生物機能としての役割についてさらに議論する。

Kinetic analysis of bird flocks

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Flying bird flocks show various kinds of behaviour such as V shape formation flight by migratory birds or "murmuration" by starlings. Recent detail observations of real flocks shed light on several properties of these collective behaviour. In this talk, we report analyses on the kinetics of black headed gull and pigeon flocks from the viewpoint of leader follower relationship.

鳥の群れの動態解析

水口　毅

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大型の渡り鳥が形作るＶ字編隊飛行やムクドリの "murmuration" のように飛行する鳥の群れは様々な形態をとることが知られている。最近の観測によって、これらの集団挙動の様々な性質が明かにされつつある。本発表では、ユリカモメの群れとハトの群れに焦点をあて、先行追尾関係という観点から群れの動態に関する解析を報告する。

群ロボットによる動的平衡な構造物の構築

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群ロボットの活躍が望まれるひとつの重要な応用例として構造物の構築があげられる．我々は，ロボットはできる限りシンプルな機能を持ち，簡単なアルゴリズムで動くようにすること，構造材料（以下，ブロックと称する）にも簡単な機能を持たせ，ロボットとブロックがお互いに協力すること，に基づいて構造物を構築する方法を提案する．構造物は鎖状に伸びることで構築されるが，その成長方向の指示はブロックがもつルールに従う．ここでは，シンプルなルールの組み合わせで基本的な幾何形状構造物の構築が可能であることを示す．また，ブロックの局所的な着脱が行われるにも関わらず，大域的には目的の形状の構造物が維持されるところがポイントとなっている．本講演では，まず基本特性を示し，続いて簡単な拡張により環境の変化に適応的に振る舞うことができることを示す．

Quorum sensing and excluded volume effects in the single and collective motion of *Dictyostelium discoideum* cells

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The dynamics and regulation of cell motility at the population scale is of great importance in various phenomena, either for unicellular - colony growth - or multicellular organisms - development, tumor invasion... We use *Dictyostelium discoideum* as a model system to study how some of the cell migration properties are affected by the collectivity. *Dictyostelium discoideum* is an amoeba that lives in forest soils. It usually follows a classical unicellular lifecycle, while feeding mainly on bacteria (growth phase). In starvation conditions, the cells aggregate and undergo a multistep developmental cycle involving signal relay, collective motion, cell differentiation and multicellular morphogenesis, eventually forms spores that can invade new environments. On one hand, the collective phenomena leading to the emergence of population dynamics in the developmental stage have been widely studied, and are still hot research topics **[1]**. On the other hand, the same cells in growth conditions (vegetative cells) have been mostly studied in isolation for their single cell properties. We have shown recently that the motility of vegetative cells is down-regulated by a quorum sensing factor (QSF) secreted by the cells that accumulates in the medium **[2]**.

Our research focuses on the rules that govern the behavior of single vegetative cells to small colonies of cells. Therefore we investigate the mechanisms of cell to cell interactions, and their role in the ensemble properties in various fresh or conditioned nutrient-rich conditions, with various mutants, using large scale time lapse microscopy, automated cell tracking and statistical analysis. On one hand, we are investigating the signaling pathways associated with this QSF response. On the other hand, to investigate the interplay of proliferation, random motion and cell-cell interactions in the collective dynamics of a population of cells, we make model circular micro-colonies of controlled shape, dimensions and density using PDMS microstencils technique **[3]**. We show that this simple system enables to record a rich set of data both at individual scale (cell division, trajectories and MSD) and at a population scale (density, fluxes, colony radius).

The spreading of the colonies is density-dependent, with an increase in spreading rate with density (Fig. 1 B,D). In addition, at short times, we clearly show the apparition of a net radial velocity**,** indicating that the spreading of the colonies cannot be modeled by simple Brownian diffusion with division. This effect may be related to “Contact Inhibition Locomotion” mechanisms already reported **[4,5]**, as well as modification of cell persistence upon contacts with other cells. The experimental results obtained were compared to individual-based simulations of active brownian particle. To be able to reproduce experimental results, active asymmetric reorientation has to be taken into account. We suggest a model where short-range interactions alone can account for short-times collective effect, while quorum-sensing factors are dominating at long times.

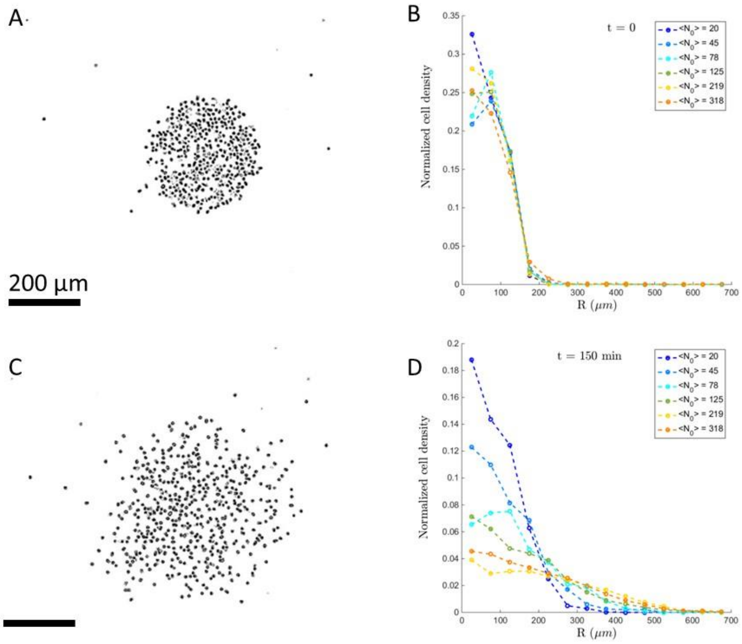

Figure 1: (A) Example of initial micro-colonies of $<N_0>=318$ cells, initial diameter is 320 µm, after image binarisation (each black dots correspond to an individual cell), **(B)** Initial normalized cell density as a function of radius R, for different initial cell number $<N_0>$, **(C)** Example micro-colonies spreading after 150 min for $<N_0>=318$ cells, (D) Normalized cell density as a function of radius R, for t=150 min.

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集団での追跡と逃避

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ここでは近年提案しました「集団追跡と逃避」のモデルについて紹介します。「おにごっこ」は多くの人が遊んだ経験のあるゲームですが、追跡と逃避の数学は３００年以上もの長い歴史を持ち、おもに１対１の状況が研究されてきました。一方では、動物、昆虫、自動車、人などの「群れ」の研究が、近年数理、物理の分野で盛んにおこなわれるようになりました。「集団追跡と逃避」ではこの二つの研究の流れを融合して、集団対集団が「おにごっこ」をするような状況をモデル化して、新しい研究課題として提案しています。集団内の個々の動きは非常に単純な場合でも、集団としては意外と複雑な様相があることを報告します。また、適度に個々の動きに揺らぎを加えると、全体のゲームの終了までの時間が最適化されるなどの「確率共鳴」的な現象が見えました。さらに遅れが加わったときにどのような状況が見えるかや、味方同士の相互作用の初期的な結果も報告します。また組合せ最適化問題などへの応用の方向などの展望も議論したいと考えます。