Mission pour les initiatives transverses et interdisciplinaires

Auto-Organisation
AAP 2021

Formulaire de candidature

Ce formulaire doit être libellé « AutoOrganisation2021_Formulaire_Nomcandidat »
et obligatoirement être déposé par le porteur ou la porteuse du projet
à la fin du questionnaire en ligne en format pdf.

Date limite de candidature : jeudi 14 janvier 2021 à midi (heure de Paris)

IDENTIFICATION

Civilité/NOM/Prénom du porteur/de la porteuse du projet		Eric CLEMENT
Section du comité national de la recherche scientifique		Section 05
Etablissement de rattachement (CNRS, Université de Nantes, CEA, etc.)		ESPCI
Code Unité (UMR, UPR, EA, etc.)		UMR 7636
Nom du laboratoire et/ou de l'équipe		Physique et Mécanique des Milieux Hétérogènes (PMMH)
Pour les unités rattachées au CNRS	Institut principal	INSIS
	Délégation régionale	Paris Centre

Projet

Titre long du projet (150 caractères maximum)	Collective bacterial dynamics in curved spaces
Acronyme du projet	BACURV

Identification des équipes travaillant sur le projet

Etablissement de rattachement (CNRS, Université de Nantes, CEA, etc.)	Code Unité (UMR, UPR, EA, etc.)	Nom du laboratoire et/ou de l'équipe	Pour les unités rattachées au CNRS		Civilité/NOM/Prénom des personnes impliquées
			Institut principal	Délégation régionale	
ESPCI	UMR7636	PMMH	INSIS	Paris Centre	Eric Clément/ Anke Lindner
ESPCI	UMR 7083	Gulliver	INC	Paris Centre	Teresa Lopez-Leon

Curriculum Vitae du porteur de projet

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Professor of Physics, Sorbonne University, Paris
Senior member of the Institut Universitaire de France (IUF)

EMPLOYMENT

2000-2021	Professor of Physics Sorbonne University, France.
1990-1999	Researcher (CR1) at the CNRS, France.
Jan-Oct.1990	Post-doctoral fellow, University P. et M. Curie, Paris, France.
Sept-Dec.1989	Lecturer in Physics, University of Michigan, Ann Arbor, USA.
1986-1989	Teaching-assistant at the University of Michigan, Ann Arbor, USA.
1985	Contractual researcher at the E.S.P.C.I., Paris.

EDUCATION

1986-1989	Ph.D. in Chemistry and in Physics, University of Michigan, Ann Arbor, USA.
1988	Master's of Science in Chemistry, University of Michigan, Ann Arbor, USA.
1984	Master in Physics of Liquids, University of Paris 6.
1980-1984	Engineering diploma E.S.P.C.I., Paris.

RESEARCH INTERESTS

- Active fluids
- Physics of granular media and rheology of suspensions
- Chemical kinetics in confined geometry
- Transport in porous media

PATENTS

DI-12082 "*Godet environnemental pour rhéomètre de Couette* **»** deposited in 2018 at the CNRS, joint PMMH UMR7636/FAST UMR 7608. Patent application n°PCT/EP2020/061961 of 29/04/2020.

CURRENT RESEARCH CONTRACTS

- Innovative Training Networks H2020-MSCA-ITN-2020 - PHYMOT « *Physics of Microbial Motility* » with Prof. A. Lindner and 13 other European groups. PI Prof. G. Gompper Forschugzentrum, Julich.

- ANR 2015-2019 - BacFlow "*Hydrodynamic transport and dispersion of bacterial suspensions: from the micro-hydrodynamic scale up to porous media*" PI E.Clément with A.Auradou and C.Douarche, Univ.Paris-Sud. End of contract extended to March 2021.

RECENT PUBLICATIONS (2019-2020)

More than 115 papers published in international journals. See list in: https://blog.espci.fr/eclement

Chirality-induced bacterial rheotaxis in bulk shear flows. G.Jing, A. Zöttl, E. Clément, A. Lindner, Science Advances, **6**, eabb2012 (2020).

3D spatial exploration by E. coli echoes motor temporal variability. N. Figueroa-Morales, T. Darnige, C.Douarche, V. Martinez, R. Soto, A. Lindner, E.Clément, Phys.Rev.X, **10**, 021004 (2020).

E.coli« super-contaminates » narrow channels fostered by broad motor switching statistics. N. Figueroa-Morales, A. Rivera, E. Altshuler, R. Soto, A. Lindner, E. Clement, Science Advances, **6**, eaay0155 (2020).

A combined rheometry and imaging study of viscosity reduction in bacterial suspensions, V. Martinez, E. Clément, J. Arlt, C. Douarche, A. Dawson, J. Schwarz-Linek, A. Creppy, V. Skultéty, A. Morozov, H. Auradou and W. Poon, Proceedings of the National Academy of Sciences, **117**, 2326-2331 (2020).

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Oscillatory surface rheotaxis of swimming E. coli bacteria ,Mathijssen, N. Figueroa-Morales, G. Junot, E. Clement, A.Lindner, A. Zöttl, Nat. Comm. **10**, 3434 (2019).

Bacterium swimming in Poiseuille flow: the quest for active Bretherton-Jeffery trajectories, G. Junot, N. Figueroa-Morales, T.Darnige, A. Lindner, R. Soto, H.Auradou, E. Clément, Europhys. Lett, **126**, 44003 (2019).

Effect of motility on the transport of bacteria populations through a porous medium, Creppy, E.Clement, C.Douarche, M.-V. D'Angelo, H.Auradou, Phys. Rev. Fluids, **4**, 013102 (2019).

PROJET DE RECHERCHE

1 - Résumé (10 lignes maximum)

Bacteria are archetypes of complex societies, where internal biochemical cascades induce intriguing individual and collective dynamics, resulting in global survival strategies, optimization of environmental resources and symbiotic interactions with other living species. Understanding these mechanisms and specifically how environmental features impact collective bacterial motion is of critical interest, non-only in

fundamental biology or ecology but also in bio-engineering or medicine. The aim of this proposal is to address the question of how bacteria explore, collectively organize and respond to stimuli in complex but controllable environments, where confinement and curvature play a central role, such as droplets, micro-sized spherical films (shells), or emulsions with complex geometries/topologies**.** We seek to produce original states of matter combining the self-assembly principles of soft matter with the inherent collective activity of bacteria using microfluidic techniques.

2 – Mots-clés (5 maximum)
Collective motion, self-assembly, geometrical confinement, bacteria, emulsions

3 - Exposé scientifique du projet explicitant les points suivants:

Motivation: Active matter describes systems in which their elementary constituents consume energy to produce motion. The interaction between these elementary active objects usually leads to fascinating collective behaviors, which are widely observed in nature at many different scales ranging from bird flocks to cellular cytoskeletons. How the behavior of the elementary active components determines the macroscopic behavior of the system is still unraveled **[Marchetti 2013]**. Micro-swimmers assemblies, such as bacteria suspensions, are model systems that allow to address some of these fundamental questions.
In natural environment, bacteria are either dispersed in fluids (planktonic state) or assembled on surfaces as biofilms. These are archetypes of complex societies where internal biochemical cascades govern the cell behavior inducing individual or collective motions. Bacterial motility is involved in survival strategies, optimization of environmental resources and symbiotic interactions with other living species. Understanding these mechanisms, specifically how environment impacts bacterial motion is of critical interest, non-only in fundamental biology or ecology but also in bio-engineering or medicine.

Objective: The aim of this proposal is to address the question of how bacteria explore, collectively organize and respond to stimuli in complex but controllable environments. In particular, we will be interested in situations where confinement and curvature play a central role, such as droplets, micro-sized spherical films (shells), or emulsions with complex geometries/topologies**.** We seek to produce original states of matter combining the self-assembly principles of soft matter with the inherent collective activity of bacteria using microfluidic techniques.

Scientific and social impact: Emulsions offer the possibility of bringing bacteria and other microorganisms to highly constrained conditions, where confinement and curvature are expected to play a crucial role in the bacterial behavior. Conversely, bacteria activity, i.e. the micro-organism motion either individual or collective, is expected to influence the space in which they are confined. For more than a decade, droplet bioreactors have been used to monitor bio-activity and to create high throughput assay conditions in order to test bioenergetic budgets or responses to drugs **[Boitard2011]**. However, quite importantly at a more fundamental level, the impact of activity on the stability of the different mesoscopic emulsion phases is not well-established yet. Recent theoretical studies suggested that the presence of activity in emulsions could be key to design new composite and hybrid materials with a strikingly rich range of morphologies **[Bonelli2019]**. This represents a potentially new and important line or research that could lead to a novel class of soft-materials shaped by activity.

In this project, we propose to use complex emulsions to systematically explore the effect of confinement and curvature on the collective organization of motile micro-organisms with the final prospect of producing original states of matter and novel materials. This project also opens exciting perspectives in terms of microbial ecology, since it will enable to test important ideas on environmental pressure selection using the possibilities offered by such controllable structures suited to perform new kinds of microbial assays.

Interdisciplinary project: The project is inherently interdisciplinary, since it requires combining expertise in: i) biochemistry and biophysics to produce bacterial suspensions with controlled properties (motility, division rate, etc), ii) hydrodynamics and statistical physics to study their collective motion, iii) microfluidics and surface chemistry to produce complex confining environments, iv) topology and geometry to analyze the patterns emerging in these constrained environments.

Complementarity of the teams: This project is jointly proposed by two ESPCI teams belonging to different CNRS institutes which developed distinct scientific activities i.e. active fluids hydrodynamics (PMMH) and topology of confined liquid crystals (Gulliver), as well as complementary experimental tools. The project is structured around the endeavor to bring together their respective expertise and propose a new and challenging line of research around auto-organization processes triggered by activity.

The **PMMH laboratory** group (Eric Clément, Anke Lindner), has intensely worked in active matter, at the interface between statistical physics, hydrodynamics and biology. This group is internationally recognized for its works on bacterial fluids and collective motion. The line of research developed in the last decade by this group aimed at revisiting some fundamental concepts underlying the physics of colloidal suspensions using bacterial suspensions as a model system. Three research axes were developed: (i) the active Brownian motion of colloids in an active bath **[Mino2011],** (ii) the transport of bacteria in confined environments **[Figueroa2015, Creppy2019, Mathijssen2019, Junot2019 Figueroa2020a, Figueroa2020b]** (iii) the emergence of constitutive properties in active suspensions **[Gachelin2013, Lopez2015]** associated with collective motion **[Martinez2020]**.

The group of Teresa Lopez-Leon at **Gulliver laboratory**, has a strong expertise in physical chemistry at the interface between soft matter, topology and microfluidics and in particular, they worked on liquid crystals self-organization in confined environments.

In the last years aimed at investigating the effect of confinement on the self-organization of soft materials. Their achievements can be grouped in four categories. (i) By using cutting-edge microfluidic techniques, they have been able to encapsulate soft materials, in particular liquid crystals, into complex micro-environments **[Lopez-Leon2011a, He2019, Kim2019]**. (ii) They have shown that geometrical frustration induced by confinement and curvature can lead to fascinating ways of self-organizing **[Lopez-Leon2011b, Darmon2016, Tran2017]** and developed a toolbox to control the way in which such systems self-organize **[Durey 2019]**. (iii) They have exploited these ideas to produce new materials with interesting applications, such as reconfigurable chiral micro-objects or micro-lasers **[Lopez-leon2011a, Amine2013, Ansell2019, Kim2019]**. iv) Very recently, they extended their studies to active materials, where the self-assembly units are not passive molecules, but active (motile) nano-objects **[Hardoüin2019]**.

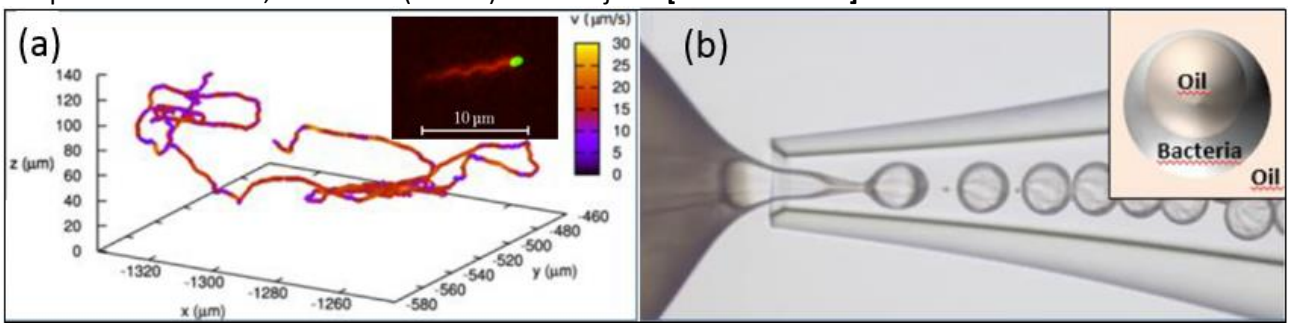

Figure 1. *(a) 3D tracking of a motile wild-type E.coli using the PMMH Lagrangian tracking device and displaying sequences of run/tumbles [Figueroa2020]. In inset, E.coli visualized and tracked in 2-colors (body and flagella) via an extension of the tracking device. (b) Microfluidic device in the Gulliver laboratory, producing double emulsions (shells) and encapsulating a suspension of E.coli. The outer droplet diameter is about 100 microns.*

Research plan: To carry out this project, we developed a research plan described below, where we highlight two crucial questions to be addressed during the duration of the present call, but which has the ambition to be extended in the future, provided the potential outcomes of this study.

I – **Combined effects of curvature and confinement on collective organization**

In the first part of this project, we will explore how confinement and curvature impact the collective motion of bacteria by confining them into micro-droplets or shells (spherical films suspended in water).

Along this line of thought, the PMMH group already has shown that, when a dense population of magnetotactic bacteria (i.e. bacteria moving along the lines of a magnetic field) is confined inside a droplet and submitted to constant magnetic field, it can self-assemble into a reversible rotary motor **[Vincenti2019]** implying collective circular motion of the bacteria (Fig.2). This intriguing behavior stems from a subtle interplay between confinement along a curved interface and swimming activity. Also, this group demonstrated

experimentally the emergence of an active "super-fluid" phase (i.e. no apparent macroscopic viscosity **[Lopez2015]**) in a suspension of dense active micro-swimmers Recently, in the frame-work of a collaboration with groups at the University of Edinburgh and at in Orsay, they have shown that the onset of collective motion is directly associated with the emergence of the "super-fluid" phase **[Martinez2020]**.

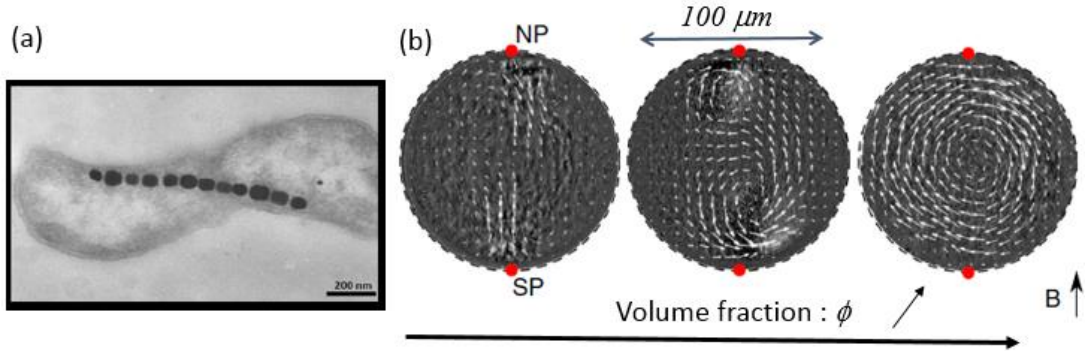

Figure 2*. Confinement of a motile magnetotactic strain : Magnetospirillum Gryphiswaldense in a water-in -oil emulsion. (a) STM image showing the ferrite nano magnets linearly assembled inside the microorganism body and bestowing magnetotactic properties. (b) Visualisation of a droplet equatorial plane at increasing bacteria concentrations, probing the emergence under a constant magnetic field B of rotary collective motion* ***[Vincenti2019]****.*

All these properties are direct consequences of large-scale hydrodynamic interactions existing between swimming bacteria acting in interplay with the nature of the confinement. This suggests that the presence of complex boundary conditions, such as those considered in this study, will significantly influence the macroscopic features of the collective swimming. Moreover, it is also very likely that in the context of soft matter emulsions, bacterial activity could significantly modify the geometry of the boundaries which might lead to novel organizational phases still unraveled.

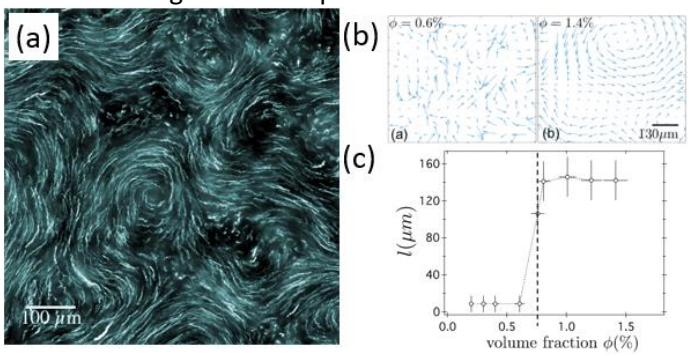

Figure 3*. Emergence of collective motion for a dense suspension of motile E.coli confined between two parallel plates. (a) Direct visualization of large-scale collective swirls. (b) Velocity field obtained by PIV, showing a stark change in fluid motion on both sides of the concentration transition at a confinement height $H = 220\ \mu m$. (c) Velocity correlation length displayed as a function of the bacteria volume fraction ϕ* **[Martinez2020]**.

In this study, we will introduce the curvature of the confining space as a control parameter in order to study and tune the collective organization of bacterial suspensions. The confining geometry will be systematically changed, non-only by producing droplets of different curvature radii, but also by producing spherical shells, where the bacteria will be confined between two nested spheres (see Figure 1b). This original geometry will allow to independently control confinement and curvature, by tuning the thickness and outer radius of the shell, respectively. To produce droplets and shells with controlled geometries, we will use glass-capillary microfluidics, a technique set by Teresa Lopez-Leon at Gulliver lab, in particular to follow the topological organization of various liquid crystalline phases **[Lopez-Leon2011a]**. We will assess bacterial motion using confocal microscopy. For increasing concentrations of bacteria, the onset of collective motion as well as its spatial extension will be determined and compared to different theoretical approaches, such as the large-scale lattice Boltzmann simulations performed in the group of A. Morozov in Edinburgh **[Stenhammar2017]** with whom we currently collaborate.

II – **Active confined thermal bath and active mixing**

In a bath of active particles, either dilute or concentrated, a passive object, being a molecular species, a nanoscale protein or a particle of microscopic size, undergoes agitation resembling Brownian motion. This generic situation is currently called an "active thermal bath". However, diffusion, collective mixing and self-organizing possibilities driven by activity, bestow on the passive objects novel emergent properties, far beyond the classical picture stemming from Brownian motion. For example, the standard fluctuation-

dissipation theorem does not hold anymore **[Burkholdera2019]**. It has also been demonstrated that it is possible to extract work from fluctuations at a fixed thermal temperature or to concentrate particles starting from an initial random distribution. All these properties are strikingly at odd with the standard outcome of equilibrium or close to equilibrium, thermodynamics **[Fodor2016]**.

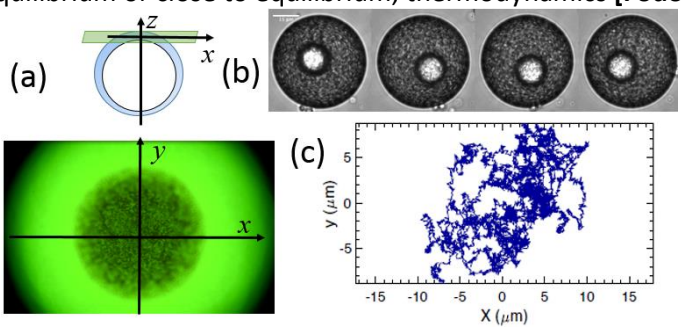

Figure 4. *Preliminary results showing suspensions of E.coli confined to a shell, visualized by confocal microscopy (Gulliver laboratory). (a) Bacterial collective motion at the upper pole of a shell (top view). (b) and (c) Random walk motion of the shell inner droplet (white circle in the 4 top images) resulting from the activity of the bacterial suspension in which the droplet is embedded (top view).*

A population of swimming bacteria trapped inside a drop or a shell will constitute an active thermal bath. The agitation properties due the swimming hydrodynamics will determine, for example, the mixing of molecular species, or could accelerate the rate of chemical reactions. Note also that, in some instances, the catalytic properties of the bacteria themselves are part of the chemical kinetics. This is an important mechanism, for instance, in clouds, where the biological activity within the droplets is thought to be a dominant factor for the cloud stability and the rain onset **[Delort2010]**. This type of active thermal bath can also favor the out-of-equilibrium organization of macroscopic objects trapped inside the droplet. Our objective is to create and study these model active thermal baths and contrast the outcome of our measurements with several propositions recently developed to describe active thermal baths in the framework of out-of-equilibrium stochastic thermodynamics (see **[Pietzonka2019]** and refs inside).

First, we will look at the fluctuating motion of an inner droplet of a shell containing bacteria when systematically changing the outer and inner radii of the shell. Then, we will characterize the motion of solid objects of different shapes trapped inside the bulk droplets. We expect to observe interesting self-organization phenomena when several of these objects are encapsulated inside the droplet. For this study, we will use the confocal microscope of the Gulliver lab mounted on a platform that can be tilted with respect to gravity. Also we will use the 3D Lagrangian tracking set-up built at the PMMH **[Darnige2017]** (see Figure 1a). Note that solid objects of different complex shapes and micron-size scale can be obtained by the 3D nano-printer of the ESPCI hosted in the PMMH laboratory.

Final remarks: This project is part of a bigger research project also involving the University of Chile, which has been only partially funded (ECOS program until 2019). We got funding from the CNRS to hire a postdoc for a year. There is also PhD student from the University of Chile who is coming to ESPCI few months this year to work on this project. This grant would allow us to provide an environment to the postdoc, the PhD student and the several undergrads we plan to involve in the project, in terms of consumables and improved environment around the microscopic techniques. We believe that the interesting synergies between the two ESPCI labs, bringing together biophysics (PMMH), hydrodynamics (PMMH) microfluidics (Gulliver) and geometry/topology (Gulliver), will allow us to unveil new states of matter paving the way for new physics and applications in biotechnology.

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BUDGET

1 – Budget détaillé et justifié par poste de dépenses et par équipe pour l'année 2021 (une page maximum). Se référer aux modalités administratives et financières précisées dans le texte de l'appel à projets. Pour rappel, le budget ne doit pas inclure la gratification de l'éventuel stage demandé.

Déplacements : missions, conférences, etc. Détail : • •	€
Organisation de manifestations : colloques, ateliers, etc. Détail : • •	€
Fonctionnement Détail : Produits et consommables pour culture biologique, • Produits chimiques 1 kE • Consommables 3 kE • •	4000€
Équipement non-amortissable (montant unitaire inférieur à 800 € HT) Détail : • •	€
Équipement amortissable (montant unitaire supérieur à 800 € HT) Détail : i) caméra E.CMOS pour visualisé les bactéries, à monter sur le microscope confocal, qui allie rapidité et sensibilité (ii) Encodeur linéaire optique pour améliorer la précision de positionnement et la rapidité de réaction d'une platine XYZ commandable montée sur le microscope. • Camera Orca Flash V4 1300 kE (Gulliver) • Encodeur linéaire XY Eidenhaim pour platine de microscope XYZ ASI (PMMH) 8 kE	21000€

• •	
Prestations de service étroitement liées à la mise en œuvre du projet Détail : • •	€
TOTAL	25000€

2 – Demande exceptionnelle d'un stage de Master. Durée : 3 à 6 mois. Cette demande doit être argumentée et le laboratoire d'accueil (uniquement les structures CNRS) doit être clairement indiqué.

VISA DU DIRECTEUR OU DE LA DIRECTRICE D'UNITE

Signature