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PhD Research Proposal

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Active Turbulence & Complex Fluids

In the last decades a number of research fields in Soft Matter have emerged, spacing from the investigation of Active Matter to the analysis of liquid crystals behaviors, intriguing the world of Physical research both from a theoretical and an experimental point of view. The basic idea of my research project is to create and investigate bindings between these fields and some theoretical issues, such as turbulence or the analysis of topological defects arising in anisotropic media.

In the next section I will briefly present the topics of my research project, then I will discuss in more detail every single point in the following paragraphs.

An overall glance. Research in the last century has brought into light plenty of connections between Physics and Biology, often leading to successfull marriages (just think to DNA discovery carried out by Crick and Watson in 1953); more recently a new field of research emerged in the attempt to describe living systems (or more in general *active* systems). The methods of statistical mechanics have been discovered to be a powerful tool for modelling and describing this kind of systems. During my thesis project, carried on with prof.Gonnella as supervisor, I faced the problem of modelling a suspension of active components, capable of exert some work in their surroundings preventing the system to relax towards its equilibrium steady state. We made use of a field-theory approach in order to define the equilibrium properties of the order parameters of the system and we coupled the theory with hydrodynamics equations; a hybrid Lattice Boltzmann Method has been implemented in order to study numerically the model in $2d$ geometries. In this manner we found that the interplay between nonequilibrium and thermodynamic forces creates a range of multifarious exotic emulsions. What is most is that flow fields consistent with turbulence profiles were found to be a common feature of our model. The analysis of such peculiar behavior deserves to be analyzed in detail for reasons that will be made clearer in the following.

Another topic in Soft Matter I will focuse on during my PhD studies, is the dynamical behavior of topological defects in polar and nematic liquid crystals in $3D$ geometries. This, far from being uncorrelated with the previous topic, involves a number of transversal issues ranging from numerical and computational implentation to advanced mathematical skills that I plan to develop in the early stage of my PhD. In particular I envisage to investigate the behavior of liquid crystals emulsions in cholesteric phase under the effect of an electric field.

In the rest of this paper I will furnish more details regarding the topics introduced so far.

Active Inverse Turbulence. Far from being close to solution, turbulence is still an open problem both in Physics and Mathematics; the fair point is that Navier-Stokes equations, governing the dynamics of fluid systems, allow for cahotic solutions whose behavior is not solvable neither analytically nor numerically. To clarify the point consider a fluid system and suppose to perturb it through some energy injection, for example exert some stress on the boundaries: if this supply exceeds a critical threshold, depending on the fluid properties, the flow will soon become irregular and unpredictable. Yet a (uncomplete) theory of turbulence was formulated by Kolmogorov in the high Reynolds number regime, and later by Ruelle and Takens under more general conditions but both are not capable to furnish a consistent explanation of the onset of turbulent mechanisms.

But what is new in active systems? Many living systems evolve in the low Reynolds number regime, far from the hypothesis of Kolmogorov theory, and for this reason stands as a good testing ground to enlarge our landscape on turbulent systems. Furthermore another peculiar aspect is worth to be taken into consideration: commonly turbulence is characterized by energy transfer from large lengthscales (where energy injection takes place) to small lengthscales (where energy is dissipated through viscous mechanisms) generating flows and vortical structures throughout the system; one refers to this phenomenum as *direct (energy) cascade*. In less common cicrcumstances the inverse process can take place: imagine to perturbate the system *locally* (for example with an oscillating tip); in this case energy injection happens on lengthscales much smaller then before and creation of flows as well of vortices implies the transfer of energy to larger lengthscales and this is why we refer to as *inverse energy cascade*. This explains the name both of this paragraph and my research project in fact, as previously stated, active matter is capable of locally injecting energy into the system and for this reason it stands as a possible experimental and theoretical way to analyze inverse turbulence; furthermore energy supply is driven by biological (or chemical) mechanisms capable of transforming chemical energy into work, and this is why this phenomenum deserves the title of *active*.

Defects Dynamics in polar and nematic systems. A topic, strongly correlated to the onset of active turbulence, is the dynamical analysis of defects both in polar and nematic systems; in fact a series of experiments on bacteria and actomyosin motility have recently demonstrated a deep link between the topological structure of the orientationally ordered constituents and flows. Indeed it seems to be possible that turbulence is driven by pairs of topological defects in the nematic pattern. Wheter this mechanism is just a different realization of a bigger universal phenomenum, turbulence indeed, or simply cahos is still an open question. Nevertheless the road toward better understanding is easy to pave (but not to run): in fact we know nothing about the $3D$-dynamics of defects in such systems; if this mechanism is the one driving tubrbulence in active nematics we expect to corroborate actual hypothesis with further and more general results.

3D numerical implementation. To solve fluid dynamics equations a wide range of methods can be implemented, from Finite Difference Algorithms to Lattice Boltzmann Methods: one goal of my first year studies will be mastering in this methods, strictly necessary for setting up a reliable numerical environment. Nevertheless a number of issues rise when you try to solve numerically fluid dynamics equations in $3D$ geometries, mostly related to time performances and memory allocations in computer infrastructures. Fortunately some possible escapes are available to avoid this kind of problems: the main idea is to split the global task into minor tasks that necessitate of less computational resources and can be accomplished making use of distributed infrastructures. During my thesis project I had trained in High Performance Computing parallelizing a code for $2D$-Lattice-Boltzmann, using MPI (Massege Passage Interface, a protocol for comunications between distributed processors in a network); now a vital requirement to perform simulations in $3D$ geometries is to develop a performant code for $3D$ fluid dynamics simulations. To reach this goal I will implement hybrid parallel computing techniques that are based on the mutual use of both CPUs and GPUs to boost the program execution.