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The Surprising Physics of Interfaces in Active Matter

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Active matter encompasses all systems in which each individual constituent independently dissipates energy in its environment. This definition brings together biological systems such as cellular tissues, bacterial colonies, cytoskeletal filaments driven by molecular motors and animal groups, as well as collections of inert self-propelled particles such as Janus particles,[1] colloidal rollers[2] or vibrated grains.[3] Because of the local persistent drive, these systems are far from thermal equilibrium and cannot be described in terms of thermodynamic potentials. This leads to surprising physics that defies some of the basic intuitions that we have from passive systems, including long-range order in two dimensions[4] and phase-separation in absence of attractive interactions.[5,6]

In this Essay, we discuss several ways in which active systems, freed from thermodynamic constraints, show a richer behavior than their passive counterparts, focusing on the physics of interfaces. We will first review the consequences of the absence of an equation of state for the pressure before turning to the different definitions of surface tension. Finally, we will close with ongoing and possible future research directions on these topics.

Pressure. The pressure is first and foremost a mechanical quantity, the force per unit area exerted by a fluid on a boundary. It is, at least in principle, directly measurable whether the system is in equilibrium or not.

In addition, in equilibrium systems, pressure has a thermodynamic definition as the derivative of free energy with respect to volume,

$$P = \frac{\partial F}{\partial V}\Big|_{N,T,\cdots}, \tag{1}$$

with the dots denoting thermodynamic variables other than particle number N and temperature T. The first law of thermodynamics then ensures that the mechanical and thermodynamic definitions agree. Importantly, because the free energy is extensive, in a large enough system, the boundaries make a negligible contribution to F and the pressure thus depends only on bulk quantities through Eq. (1), the equation of state. This implies that the force exerted by (say) a liquid is the same, independently on what it is exerted on, for example a container, another part of the fluid or a coexisting vapor phase.

In active systems, on the contrary, there is *a priori* no equation of state. One should then measure a different mechanical pressure depending on the instrument used to measure it, e.g., probes made of different materials. This is indeed what was observed in models of self-propelled particles when the interactions do not conserve momentum (for example because of aligning or chemically-mediated interactions)[7,8] and experimentally for vibrated disks confined by a chain with tunable stiffness[9] and should be kept in mind when discussing experimental measurements, for example of the viscosity of a bacterial suspension[10] or the mechanical stress in cell tissues,[11] which are expected to depend on the measurement method. In systems with momentum-preserving interactions, e.g., spherical particles interacting via pairwise forces, a mechanical pressure can still be defined, independent of the measurement instrument.[7,8]

Another consequence of the absence of an equation of state is that the two coexisting phases in motility-induced phase separation (MIPS)—when particles which tend to propel slower in denser environment separate into a low-density motile phase and a high-density arrested phase—can have different mechanical pressure.[8] Moreover, the coexisting densities depend on how the two phases interact,[12,13] whereas in passive phase separation the phase diagram depends only on bulk quantities. In addition, the pressure on a wall generically depends on its curvature, even for non-interacting self-propelled particles.[14,15] This leads to a buckling instability for flexible filaments embedded in a bath of active particles.[9,15]

Surface Tension. In equilibrium systems, at the level of thermodynamics, an interface is fully characterized by a unique coefficient, the surface tension γ defined as the cost in free energy for creating a unit area of interface,

$$\gamma = \frac{\partial F}{\partial A}\Big|_{V,N,T,\cdots}, \tag{2}$$

where A is the area of the interface. The surface tension is connected to various aspects of the mechanics of

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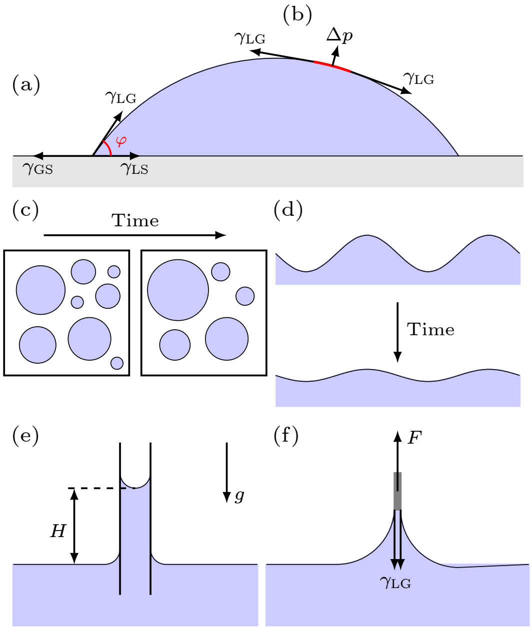

Fig. 1. In equilibrium, surface tension controls different properties: (a) The contact angle φ for a liquid droplet partially wetting a solid surface given by the Young–Dupré law, the force balance of the three surface tensions: liquid-gas γ_{LG}, liquid-solid γ_{LS}, and gas-solid γ_{GS}. (b) The Laplace pressure difference Δp between the two sides of a curved interface. (c) The coarsening whereby, when a system contains multiple droplets of different sizes, the small ones dissolve into larger ones. (d) The relaxation time of capillary waves at liquid-gas interfaces. (e) The capillary rise H of a liquid into a tube against gravity. (f) In Wilhelmy's experiment, the force exerted on a thin plate slowly pulled out of a liquid.

interfaces[16,17] as depicted in Fig. 1: it controls the wetting of a solid surface by a liquid drop through the Young–Dupré law [Fig. 1(a)], the Laplace pressure [Fig. 1(b)] that drives the coarsening dynamics of a phase separating fluid [Fig. 1(c)], the relaxation of capillary waves [Fig. 1(d)], the capillary rise [Fig. 1(e)] or the force exerted in the Wilhelmy plate experiment [Fig. 1(f)]. Importantly, the stability of the system requires $\gamma > 0$, otherwise the system would spontaneously create interfaces.

As for the pressure, in active systems there is no thermodynamic definition that unifies the different phenomena shown in Fig. 1 so that, in general, they each depend on the microscopic details of a particular situation. For a given interface, there is thus not only one surface tension but possibly several quantities controlling different phenomena. Most interestingly, some of them can be negative, leading to new physics.

Let us first consider the interface between coexisting phases in MIPS. It was found that, at least at the mean-field level, analogues of the stress tensor and pressure control the phase equilibrium[13] although they cannot be interpreted as measurable forces. One can then define a "mechanical" surface tension as the excess of this pseudo-stress at the interface that controls the Laplace pseudo-pressure jump[13] and thereby the coarsening dynamics.[18] For self-propelled particles interacting via a short-ranged pairwise repulsion, a system exhibiting MIPS when the particles are sufficiently persistent, this surface tension was measured negative.[13,19] As a consequence, one expects to see a reversed Ostwald ripening either for liquid droplets or gas bubbles (but not both).[18] The latter is observed in microscopic models which means that two bubbles of gas immersed in the liquid phase tend to equalize their size. In practice, for small enough systems, it leads to a complex steady-state dynamics termed "bubbly phase separation" where bubbles are continuously created inside the liquid phase and expelled into the outside gas,[18] showing a scale-free distribution of bubble sizes.[20,21] In large enough systems, it gives way to an homogeneous bubbly liquid which is a microphase separation between the liquid and gas bubbles with a finite characteristic size.[21]

For MIPS, even when the mechanical surface tension is negative, one observes stable interfaces, suggesting that the relaxation of capillary waves at the interface is controlled by a different quantity. Indeed, the capillary interfacial tension was measured positive from the spectrum of the fluctuations in interface position.[22] In Active Model B+ (AMB+), the scalar field theory relevant to describe MIPS, the mechanical[18] and capillary[23,24] surface tensions are clearly different quantities. Strikingly, in some parameter regimes the capillary tension can become negative leading to new physics, including an "active foam state".[23] There remains to see if this phenomenology can be observed also in microscopic models.

Looking at the wetting of a solid surface by a drop of active liquid,[25–30] one would naively expect that the contact angle is controlled by the mechanical surface tension, as in passive systems. However, in cases when it is negative, it would lead to a complete dewetting, at odds with numerical observations that exhibit partial wetting.[27,28] It was recently shown that the mechanical surface tension do enter in the force balance at the contact point but that currents generated by the interface also make an essential contribution, leading to an active Young–Dupré equation[28] determining the contact angle. Such currents are generic in active matter, generated by any asymmetric object embedded in an active bath, and long-ranged, decaying algebraically with distance.[31–34] Their amplitude depends on the details of the interactions and geometry, which leads to different contributions to the force balance on a droplet of liquid partially wetting a solid,[28] the force exerted on Wilhelmy's plate,[28] the force exerted on a junction between two materials in a Langmuir setup[35] and the capillary rise against gravity.[36,37] In addition to participating in the force balance, the currents lead to new phenomenology, for example limiting the size of adsorbed droplets.[28]

Finally, it was recently found that, in most models, the ordered phase of collective motion is actually metastable to the spontaneous nucleation of defects. This was observed in the Vicsek model,[38] although in only part of the phase diagram, and for any parameters in the active Ising model[39] and a constant-density Toner–Tu equation.[40] In all these cases, a large enough (but finite-sized) initial fluctuation triggers a growing excitation that destroys the ordered phase. We hence see that, in these systems which are the active counterparts of the equilibrium Ising and XY models, there does not seem to be any “cost” for creating or extending an interface. One should thus forget about the concept of surface tension as an energetic barrier for creating interfaces when thinking about active systems.

Outlook. In this Essay, we emphasized how in active matter, unconstrained by thermodynamics, pressure need not obey an equation of state and several surface tensions controlling different aspects of interfaces can coexist. We briefly described some of the intriguing phenomena that this allows.

These phenomena were all recently discovered, and our understanding remains incomplete. To cite just a few outstanding questions regarding the physics shown in Fig. 2: (i) The distribution of bubble sizes in bubbly phase separation [Fig. 2(a)] is a matter of debate as it was measured to be algebraic in microscopic systems[20,21] but not in the AMB+ field theory.[41] This has important consequences regarding the large-scale behavior of the system, with phase separation surviving only in the latter case, which questions the relevance of AMB+ as the appropriate field theory to describe microscopic models of self-propelled disks. (ii) The active foam state shown in Fig. 2 was observed in the AMB+ field theory, where the parameters do not have a clear physical meaning. There remains to understand which ingredients, if any, could lead to such phenomenology in a microscopic model or experiment. (iii) The active currents depicted in Fig. 2(c) lead to complex dynamics involving merging and splitting of adsorbed droplets,[28] which remain to be characterized. In particular, we do not understand at this moment how a typical size is selected for adsorbed droplets.

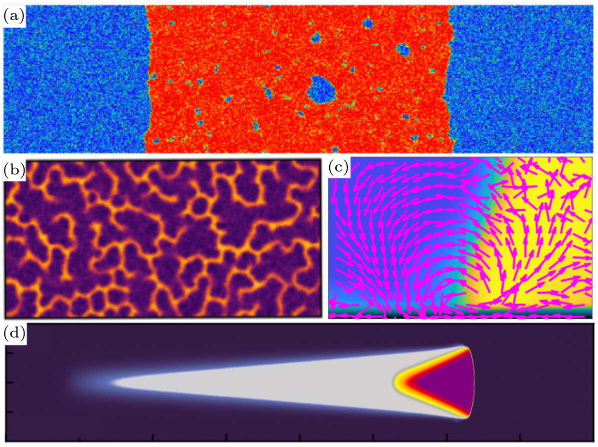

Fig. 2. (a) Bubbly phase separation for repulsive active Brownian particles[21] with negative mechanical surface tension. (b) Active foam in AMB+ with negative capillary interfacial tension.[23] (c) Contact region of a droplet of active Brownian particles partially wetting a solid surface at the bottom. The pink arrows indicate the direction of the particle currents generated by the interface.[28] (d) A small initial perturbation in the ordered phase of the active Ising model grows ballistically in time, ultimately destroying the order.[39] In (a)–(c), warmer colors code for higher density. In (d), the surrounding dark blue code for negative magnetization (i.e., left-moving particles), warmer colors denote a positive magnetization (i.e., right-moving particles), increasing from yellow to purple. The gray region is empty.

(iv) In the Vicsek model, the ordered phase is seen to be metastable only at intermediate noise values. At low noise, propagating droplets [similar to those in Fig. 2(d)] seem to be prohibited; thus, the ordered phase becomes stable for reasons that are currently under investigation. Moreover, definitions of surface tension themselves are still a matter of debate within the community and several others have been proposed in the literatures.[42–46]

The question of the fluctuations of active interfaces is another topic that should continue to draw attention. For MIPS, so far all measurements have concluded that the scaling of fluctuations is compatible with the Edwards–Wilkinson universality class.[22,47,48] However, it was argued from the AMB+ field theory that there are relevant nonlinearities such that the interface should belong to a new $|\boldsymbol{q}|$KPZ class.[49] More work is necessary to reconcile theory and simulations.

Compared to pressure and surface tension, the chemical potential has been much less studied for active systems. In the same way, one expects that, because thermodynamic relations do not apply, different definitions of chemical potential that usually coincide will yield different answers. It would be interesting to explore which quantities are most relevant, in particular to describe mixtures of active and passive particles or different species of active particles.

More generally, our theoretical knowledge of the physics of interfaces in active matter is limited to certain classes of systems. Most of the results presented here concern the simplest class of scalar active matter,[34] systems that can be described in terms of only a density field. Aligning self-propelled particles that exhibit collective motion fall outside of this class and little is known about their interfacial properties. The influence of boundaries has been found to be non-local, for example leading to strong Casimir-like forces[50] or edge currents in chiral systems,[51–55] while the coupling with chemotaxis can lead to interfacial instabilities,[56,57] but much remains to be explored. Moreover, all the examples discussed in this Letter concern “dry” active matter in which the particles exchange momentum with a substrate. In practice, many active particles such as bacteria or colloidal rollers[2] live in water and are hence subject to hydrodynamic interactions. The effect of a momentum-conserving fluid on the phenomenology presented here and whether new effects arise thus constitute important open problems.

To conclude, we have made clear that, compared to passive systems, the thermodynamic quantities usually obeying equations of state are each replaced by several quantities that depend on different microscopic details. This non-universality may seem disappointing to a physicist but, looking forward, it might turn out to be active matter’s blessing. The fact that interactions at boundaries and interfaces can affect the bulk behavior offers new possibilities for controlling the system. As an example, rough boundaries have been found to suppress motility-induced separation for self-propelled disks, even in arbitrarily large systems.[58] It is easy to imagine that more complex systems, including active viscoelastic fluids and biological systems, could offer a greater range of possible behaviors to be tuned from the boundaries, possibly with practical use.

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