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Hydrodynamics of driven and active colloids at fluid interfaces

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Driven and active colloidal systems exhibit unique and useful behaviors such as collective motion and enhanced mass transport. While these systems are well-studied in bulk fluids, less is known about their behavior under the influence of boundaries, which can strongly alter the motion of nearby colloidal particles and the fluid flows they generate. In this work, we quantify the flows generated by driven and active (i.e., self-propelled) colloidal particles at fluid-fluid interfaces by developing an appropriate flow singularity model, focusing on the leading-order modes most influential to hydrodynamically induced mixing and interparticle interactions. We consider both externally driven and active particles (microswimmers) either adjacent to or adhered to the interface. In the latter case, we assume a pinned contact line. The Reynolds and capillary numbers are assumed much less than unity, in line with typical micron-scale colloids involving air- or alkane-aqueous interfaces. At clean (surfactant-free) interfaces, the hydrodynamic modes are essentially a restricted set of the usual Stokes multipoles in a bulk fluid. To leading order, driven colloids exert viscosity-averaged Stokelets parallel to the interface, while active colloids drive different kinds of fluid motion depending on their orientation with respect to the interface. We then consider how these modes are altered by the presence of an incompressible surfactant layer, which occurs at high Marangoni numbers. This limiting behavior is typical for colloidal systems at small capillary numbers, even when scant surfactant is present. Compared to a clean interface, incompressibility substantially constrains flow directed normal to the interface. For both driven and active colloids, this flow arises only from asymmetry of the colloid geometry or boundary motion with respect to the interfacial plane. The flow parallel to the interface is also restructured dramatically. Moreover, surface-viscous stresses, if present, potentially generate very long-ranged flow on the interface and the surrounding fluids. We examine the limiting forms of such flows. Our results have important implications for colloidal self assembly, collective behavior, and enhancement of advective mass transport near fluid interfaces