Liquid Flow Driven by Light Scattering

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Background

Water-in-oil microemulsion with two surfactants.

Above a critical temeprature $T_c \approx 35\,^\circ$C, fluid separates into two phases with different micelle concentrations: Φ_1, Φ_2.
$\Rightarrow$ Phases have different densities and indices of refraction.

The phase separation is a second-order phase transition. Many fluid properties scale like power laws in $\Delta T \equiv T - T_c$:

- Difference in micelle density: $\Delta\Phi = \Delta\Phi_0(\Delta T/T_c)^{0.325}$
- Surface tension: $\gamma = \gamma_0(\Delta T/T_c)^{1.26}$
- Osmotic compressibility: $\chi_T = \chi_T^0(\Delta T/T_c)^{-1.24}$

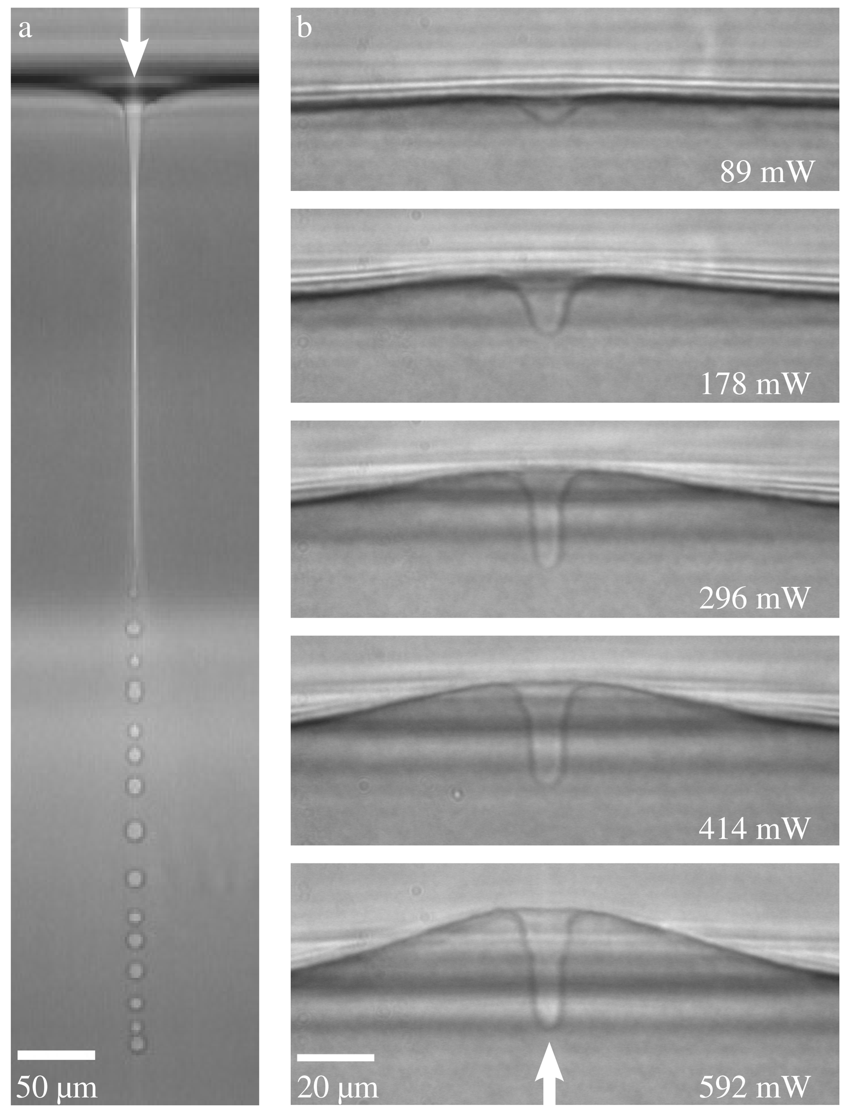
Surface tension is 10^{-6} air-water interface
$\Rightarrow$ Surface can be easily deformed by radiation pressure from a laser

This radiation pressure results from the change of the momentum of a photon as it passes the interface. In this system, the radiation pressure always deforms the interface downwards.

The laser delivers up to 1 W of power in a Gaussian beam profile with width $\omega_0 = 3 - 15\,\mu$m. See Casner and Delville, PRL **87** 054503 and PRL **90** 144503.

Motivation

Evidence of flow in two regimes



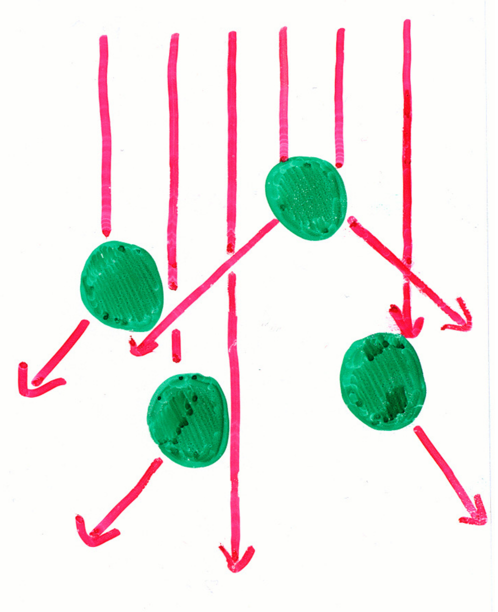
a) Laser beam from above deforms interface into jet. The tip of this jet emits a stream of droplets which travel downwards.

b) Laser beam from below produces a downwards tether. Additionally, a large-scale upwards hump forms. The radial extent of this hump does not depend on the material parameters or the laser. This suggests it could be the result of a flow whose size is set by the container.

What drives this flow?

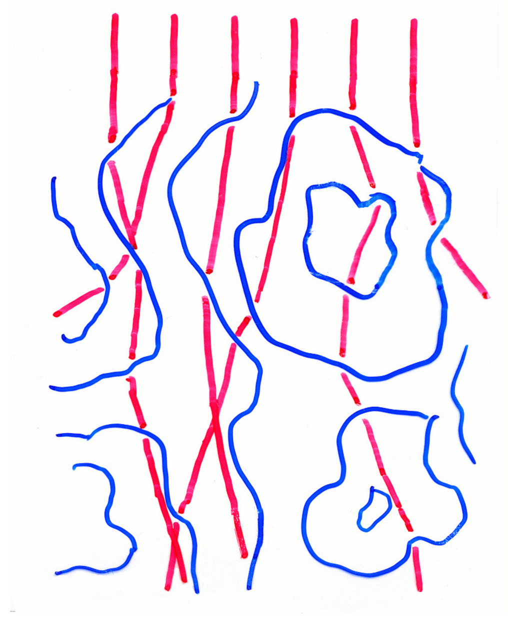
Force Due to Light Scattering

Light scatters off of objects with a different index of refraction than their surroundings. As the light scatters away from its propagation direction, its forward momentum decreases. This momentum is transferred to the fluid, where it acts as a body force. Thus, light scattering in a fluid can drive a flow.



Typically, this scattering is off small objects suspended in the fluid. In this system, the micelles will scatter some light and produce a body force.

However, this effect is dwarfed by scattering off of density fluctuations.



Because this fluid is near a second-order phase transition, it experiences fluctuations in its order parameter, the micelle density. These create fluctuations in the local index of refraction, which scatter light.

This scattering is described by Ornstien-Zernike theory. The resultant force per unit volume for light of intensity I is

$$F_v = D\,\chi_T\,I$$

where

$$D = \frac{\pi^3 n}{\lambda^4 c}\left(\Phi\frac{\partial\epsilon}{\partial\Phi}\right)_T^2 k_B T \alpha^{-4}\Big[\tfrac{8}{3}\alpha^3 + 2\alpha^2 + 2\alpha - \left(2\alpha^2 + 2\alpha + 1\right)\ln(1+2\alpha)\Big]$$

$\alpha \equiv 2(2\pi\, n\,\xi/\lambda)^2$
$n = \sqrt{\epsilon}$ is the index of refraction
ξ is the correlation length
λ is the vacuum wavelength of the light

Near T_c: χ_T, diverges $\Rightarrow F_v$ becomes large.

Density fluctuations
$\Rightarrow$ Light scattering
$\Rightarrow$ Large-scale flow

Small-Scale Light-Driven Flow

The force per unit volume F_v acts like a pressure gradient on the fluid. Since the flow is viscous, it is balanced by viscous dissipation:

$$F_v \sim \mu\nabla^2 u \sim \mu u/{\omega_0}^2$$
$$\Rightarrow u \sim F_v\,{\omega_0}^2/\mu$$

Light intensity $I \propto P/{\omega_0}^2$, for a laser with power P.

$$F_v = D\,\chi_T\,I \propto D\,\chi_T\,P/{\omega_0}^2$$

The centerline velocity of the flow in the beam is

$$u_0 = C\,D\,\chi_T\,P/\mu$$

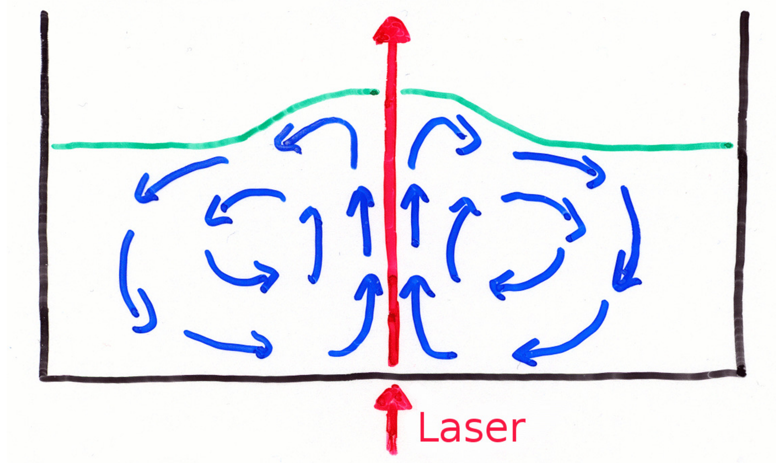
where C is a dimensionless constant describing the geometry of the container.

Velocity is only dependent on total laser power and is independent of the beam width.

Large-Scale Recirculation

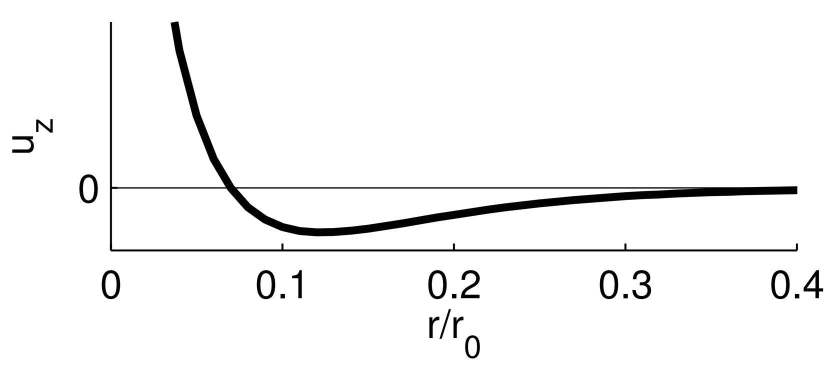
This fluid driven along the laser beam must recirculate upon reaching the edge of the fluid layer, because of mass conservation. When the laser shines from below, the lower fluid is driven upwards along the beam and recirculates downwards away from the beam.

Light-driven flow $\Rightarrow$ Large eddy



We have developed an analytical solution for a single toroidal recirculation, corresponding to an eigenfunction meeting these boundary conditions, which accurately model the spatial structure of the flow:

- Cylinderical container of depth 1 mm and radius $r_0 = 5$ mm.
- No-slip boundary conditions on cyliner.
- Free-surface boundary conditions on top and bottom.



The vertical velocity u_z at the midplane of the layer shows the expected structure: flow upwards at small r and downwards at larger r.

Interface Deformation

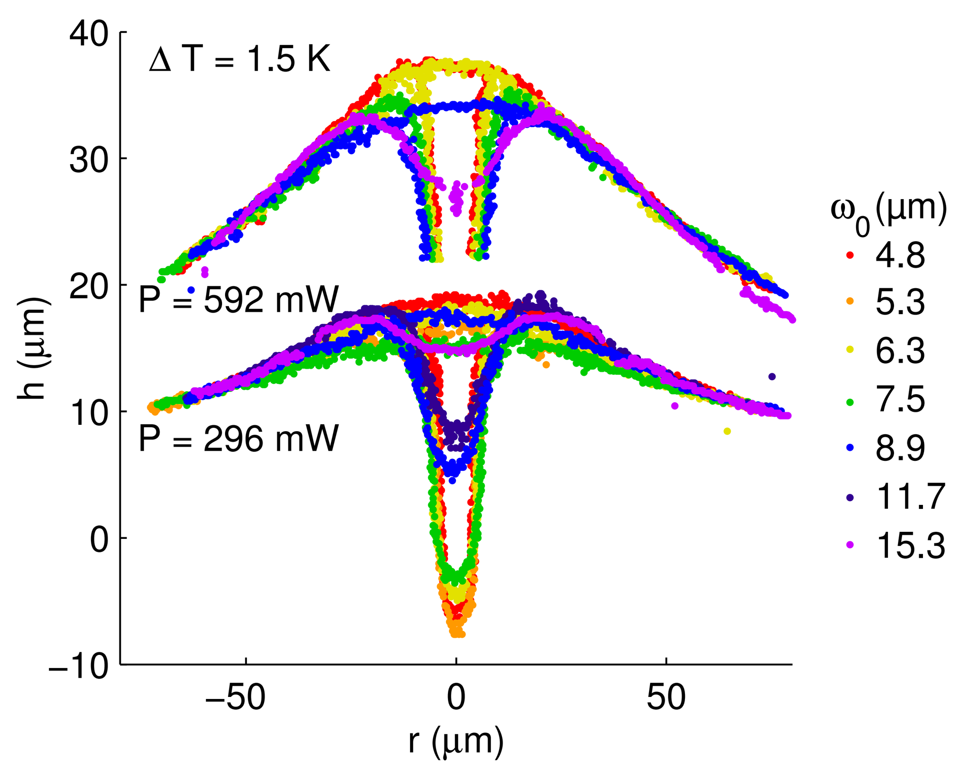
The large-scale recirculation flow will produce a normal stress on the interface between the two fluid phases. The stress will deform the surface until it can be balanced by surface tension and buoyancy. The height of the interface from its resting position, $h(r)$, must satisfy

$$-\gamma\left[\frac{h''}{1+(h')^2} + \frac{h'}{r}\right] + \Delta\rho\,g\,h = -\sigma_{zz}$$

where σ_{zz} is the normal stress on the interface from the flow, $\Delta\rho$ is the difference in densities, and g is gravity.

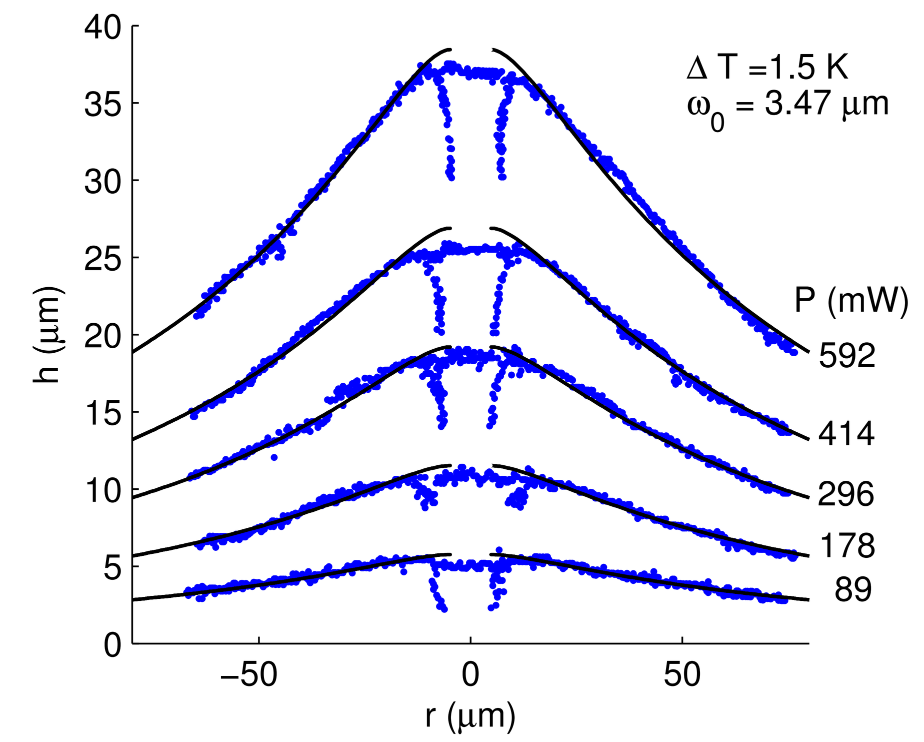
Since the flow caused by light scattering depends only on the laser power and not on the beam width, the humps formed at a given power and different beam widths have the same shape away from the beam axis.

Hump profiles for different ω_0



Given the viscous stress from the recirculating flow, we numerically solve for $h(r)$. To mimic the effects of radiation pressure, which creates the downwards tether, we use the boundary condition $h'(\omega_0) = 0$. Fitting one value of C produces good agreement at all powers.

Hump profiles and interface solutions



Light scattering induces a large-scale flow in the fluid.