Laser Tractor-Beam of 2D Flow in Soap Films

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Abstract: We present the first observation of laser tractor-beam of 2D flow in soap films.

Soap films offer many interesting phenomena from 2D chaos to recently discovered branched flow of light [1], moreover the forces the light applies to the films may cause flow. When a light beam scatters off a particle, part of it usually reflects back and momentum is transferred to the particle in the direction of the beam propagation. This is the essence of radiation pressure, discovered by Kepler in 1619, in attempt to explain why the long tail of a comment points away from the sun. This is the natural action of light on particles. A tractor beam is a beam that does the opposite: it attracts rather than pushes particles. Apparently this idea originates from science fiction, yet in the past 20 years it received much attention – not only by Star Trek fans - but also in the scientific community. The first experiments of trapping particles by gradient force and radiation pressure were done by Ashkin back in the 70's and 80's [2,3]. It was later suggested [4] that acoustic Bessel beams have regions with negative radiation pressure and are capable of pulling particles, with demonstration for acoustic [5] and optical beams [6,7]. Additional techniques such as solenoid beams [8], Gaussian beam superpositions [8], polarization controlled tractor-beams[9], beams in judiciously designed anisotropic crystals [11], and more were proposed, where the beam pulls particles. Altogether, all of the research done so far on using light to pull particles has focused on momentum transfer to particles alone. In contrast, we study optical forces on thin liquid membranes, in particular, how a laser beam can generate two-dimensional flow in these films when it propagates inside the membrane. We find that a laser beam pulls the liquid and generates flow in the direction opposite to the beam, in other words, towards the source, creating a flow tractor-beam.

Here, we present the first experimental study of a laser tractor-beam of 2D flow in soap films. We couple an optical laser beam into a thin liquid soap film doped with coffee compounds (glycerol, detergent and coffee molecules) and study both the beam dynamics in the membrane as well as the effect it has on the membrane. Interestingly, we find that the light induces flow in the membrane towards the source, effectively attracting the medium itself together with particles in it. We find that the effect only occurs when the film is doped with absorbing particles – coffee compounds, which interact with the light and change the properties of the membrane as a result.

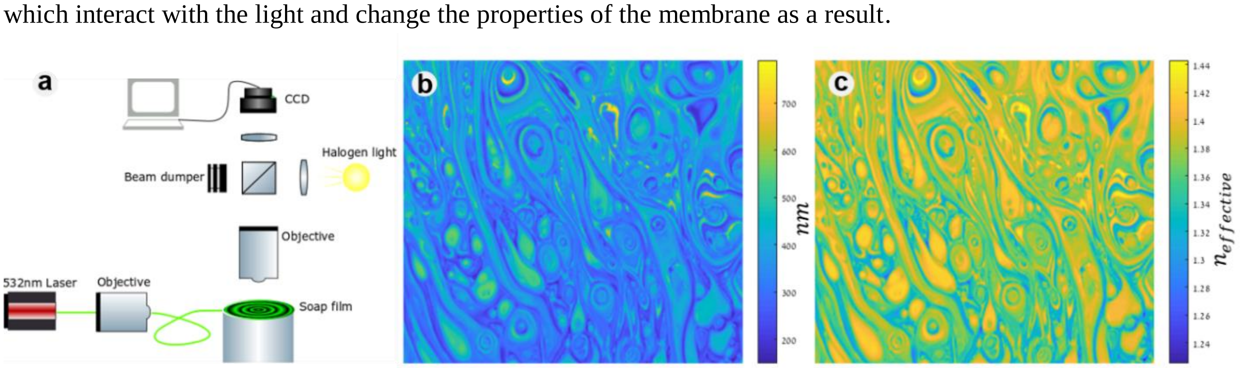

Figure 1: (a) Schematic representation of the setup. The laser beam is focused by an objective into an optical fiber. The fiber is injected into the soap bubble and as a result the laser beam is coupled into the soap film which is essentially a 2D membrane. To image the flow in the membrane, the soap film is illuminated by white light from the top. The reflection indicates the thickness structure of the film and the thickness variations due to flows. We observe the thickness variations in the membrane, the flow in the membrane, and the propagating laser beam, through the microscope. (b) Thickness structure of the film as extracted from the reflected light. (c) Corresponding effective refractive index of the film shown in (b).

The experimental setup is shown in Fig.1a. A laser beam (532nm CW) is coupled to an optical fiber so that it can be easily injected into the membrane. As a result, the laser beam is coupled into the film, acting as a 2D slab waveguide inside which the beam propagates. The film is illuminated from the top by white light and the reflection is recorded by a CCD camera. From the reflection image it is possible to reconstruct the thickness structure of the film (Fig 1b). From the thickness structure, the effective refractive index is calculated, Fig.1c. This effective refractive index the light experiences, is dictated by the thickness landscape of the film and affects the propagation of the beam in the film. A typical propagating beam and the reflected white light pattern revealing the thickness variations of the film are shown in Fig. 2a. The color variations correspond the thickness variations.

This setup allows us to carefully monitor and observe the variations in the film and the beam, thus revealing their dynamics. Initially, before the laser is turned on (t=0, Fig. 2b), the film is relatively static and does not display any flow. Once the laser is turned on and the beam begins propagating inside of the film (t=1-5[s], Fig. 2c-f), we notice that the light induces flow in the liquid film, and its direction is towards the light source (opposite to the direction of beam propagation). The effect can be seen by following movement of the different features of the film width from frame to frame. The light beam attracts the medium itself together with everything inside it (in this case, small particles). In order to make the flow noticeable, some thickness variations are marked by a white arrow and are traced from frame to frame (c-f). The initial location of the features is marked by a white circle and the location of the initial feature is marked by a white arrow in each frame. The characteristic velocity of the flow is $1mm/sec$. The naïve expected behavior is for the beam to cause flow in the same direction it propagates, as a result of radiation pressure. Counterintuitively, the opposite happens. The flow we see is a result of the interaction between the light and the absorbing coffee compounds, and does not appear without the doping. However, the mechanism of this attraction is not clear yet, and we suspect it is a result of variations in the surface tension and heat flow in the film. Moreover, we found that the velocity of the flow increases for higher laser powers.

This observation of flow tractor-beam provides insight on the nature of flow driven by light in thin liquid films. We show that it is possible to attract objects in the liquid by generating flow towards the source. We are actually able to attract particles in the liquid to very large distances - on the order of centimeters.

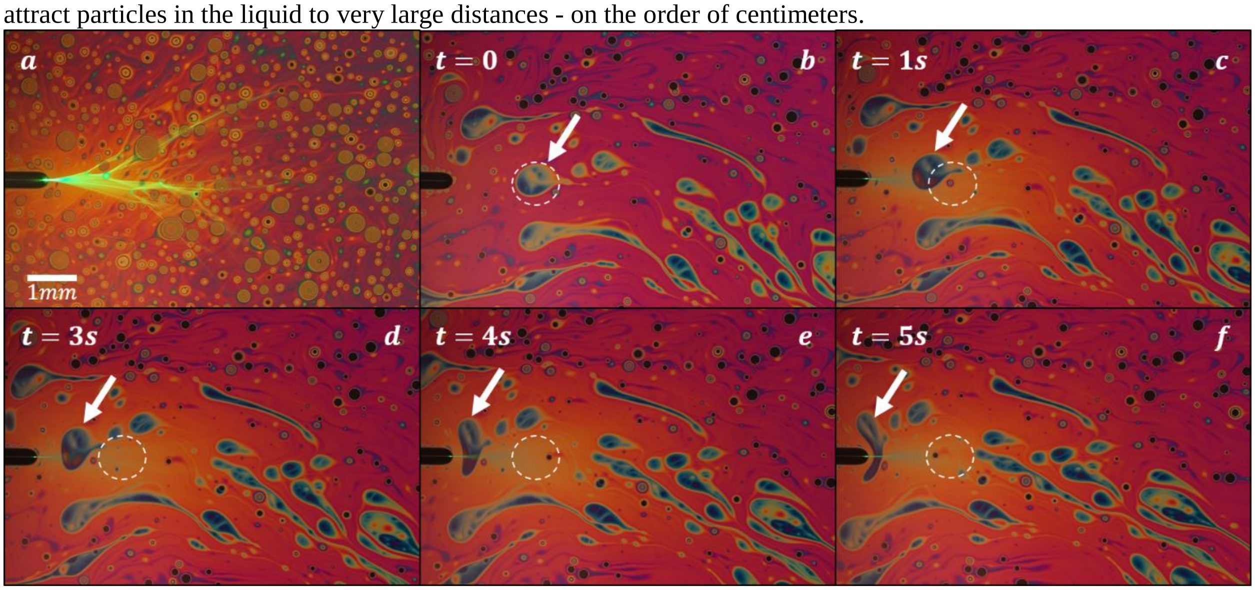

Figure 2(a) Characteristic propagating beam in the soap film. In figures c-f the beam is barely seen because it is much weaker than the reflected light from the film. This technique is applied to observe mainly the flow pattern of the film. (b) Initial state of the film, no flow, the membrane is static and the laser is off. (c-f) The evolution of the flow as function of time. Each figure is a time step of 1 second. In figures c-f the beam is injected into the membrane and flow towards the source is generated. It is shown how the features of the film evolve and getting closer to the optical fiber. The flow is attracted toward the source of light.

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