SWIRLED BY LIGHT

A micron-size particle immersed in a liquid can be trapped by light. Experiment shows that the trapping can be accompanied by whirling, with the direction of circulation varying with the light intensity.

The spectacular progress of the last few decades in manipulating tiny objects, from micron-size particles to bacteria to DNA molecules, is associated with the development of optical tweezers[1,2], an instrument which uses strongly focused laser light for trapping objects and then moving them at will. The stiffness of optical tweezers is limited, and optically trapped particles do not reside at the trap center but rather wander about it. Such wandering is a consequence of thermal fluctuations and a counterpart of random motion of free particles floating in a liquid, the Brownian motion whose explanation by Einstein in 1905 was one of the triumphs of physics of the early 20th century.

In a recent paper[3] Sun *et al*. report that the trajectories of optically trapped colloidal particles, although random, can nevertheless display a complicated pattern. It has a circulatory bias, i.e., the streamlines obtained by averaging the recorded trajectories are rotating. The corresponding circulation of the probability current was called by the authors a Brownian vortex[3]. It was found that the direction of the rotation and the overall streamline pattern depend on the light intensity, with possible coexistence of counter-rotating rolls.

Not only is the streamline circulation interesting in itself, but this is also a profound indication of the fact that the optically trapped particles studied in the experiment were away from thermal equilibrium. The flux was found in a stationary optical trap[3], in contrast to directed motion seen before[4] in traps formed using periodically modulated radiation.

The absence of macroscopic fluxes is a fundamental property of thermal equilibrium systems. Such fluxes would dissipate energy; therefore, they would decay with no energy input from the outside, characteristic of thermal equilibrium. On the other hand, nonequilibrium systems that gain energy from external sources should generally display fluxes. The occurrence of a stationary flux in the configuration space is compatible with the probability distribution of the system being independent of time, as long as the flux divergence is zero. For optically trapped transparent colloidal particles in thermal equilibrium, the stationary probability distribution has been studied in detail[5,6].

One can conditionally separate nonequilibrium flux-carrying systems into two large classes. One is formed by systems in which a flux does not require fluctuations once formed. A well-known physical example is a laser: once a laser starts radiating, the primary effect of fluctuations is decay of the radiation coherence. Formally, such systems have stable limit cycles or more complicated nonstationary stable dynamical states. In the other class of systems, external driving is unable to support a stationary flux on its own. The very occurrence of the flux is due to fluctuations[7]. It is to this class that the colloidal particles studied in the experiment[3] are related.

An insight into the onset of a fluctuation-facilitated flux can be gained from Fig. 1. Back in 1953 Onsager and Machlup noticed[8] that, for an equilibrium colloidal particle, the most likely trajectory of moving to a given state can be obtained from the most likely trajectory of moving from this state by time inversion. Therefore, most probably, the particle arrives at a state with the velocity opposite to the one with which it leaves this state, and then there is no net flux. In contrast, the trajectories of nonequilibrium systems are not related by time-reversal symmetry, their velocities at a given state are different, and this leads to the onset of a flux. The difference between the most probable trajectories to and from a given state of a nonequilibrium system has been seen in analog simulations[9] and experiment[10].

The observation of a stationary flux and its complicated structure[3] provides an important insight into the physics of systems away from thermal equilibrium and the features of their behavior that have no analog in thermal equilibrium systems. The trajectory-based approach is advantageous for gaining such insight because of its sensitivity to the system dynamics. In the context of optical tweezers and their applications, the experiment of Sun *et al.*[3] raises questions about the nature of the forces in an optical trap, and in particular about the reason these forces may become nonconservative.

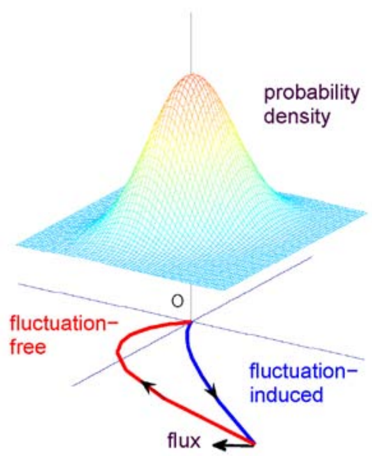

Figure 1. Stationary fluxes in thermally nonequilibrium systems. The upper panel shows the stationary probability distribution of a particle as a function of coordinates. It is maximal at the stable stationary state *O*. In the absence of fluctuations, the particle will move toward *O*; deviations from *O* are due to fluctuations. Sketched are examples of the most probable trajectories to (fluctuation-induced) and from (fluctuation-free) a given state. The stationary flux at a given state is determined by the sum of the velocities on these trajectories at this state.

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1. Ashkin, A., Phys. Rev. Lett., **24**, 156-159 (1970**).**

2**.** Ashkin, A., Dziedzic, J., Bjorkholm, J. & Chu, S., Opt. Lett., **11**, 288-291 (1986).

3. Sun, B., Lin, J., Darby, E., Grosberg, A. Y. & Grier, D. G., Phys. Rev. E, **80,** 010401 (2009); a spurious inward spiralling of the streamlines is addressed by the authors at http://physics.nyu.edu/grierlab/sampledvortex

4. Faucheux, L. P., Bourdieu, L. S., Kaplan, P. D. & Libchaber, A. J., Phys. Rev. Lett., **74**, 1504-1507 (1995).

5. Florin, E.-L.; Pralle, A.; Stelzer, E. & Hörber, J. Appl. Phys. A, **66**, S75-S78 (1998).

6. McCann, L. I., Dykman, M. & Golding, B., Nature, **402**, 785-787 (1999).

7. Tomita, K. & Tomita, H., Progr. Theor. Phys. **51**, 1731-1749 (1974).

8. Onsager, L. & Machlup, S., Phys. Rev. **91**, 1505-1512 (1953).

9. Luchinsky, D. G. & McClintock, P. V. E., Nature, **389**, 463-466 (1997).

10. Chan, H. B., Dykman, M. I. & Stambaugh, C., Phys. Rev. Lett. **100**, 130602 (2008).