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Optical levitation and long-working-distance trapping: From spherical up to high aspect ratio ellipsoidal particles

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ABSTRACT

Radiation pressure forces from a moderately focused vertical laser beam are used to levitate transparent particles, a few micrometers in size. Having recalled basic results about levitation of spheres, and applications to long-working distance trapping, we turn to ellipsoid-shaped particles. Experiments are carried out with polystyrene particles, inside a glass chamber filled with water. The particles are lifted up to contact with the chamber top surface. We examine particle equilibrium in such conditions and show that the system "bifurcates" between static on-axis equilibrium with short ellipsoids, to sustained oscillations with longer ones. A similar Hopf bifurcation is found using a simple ray-optics model of the laser-ellipsoid interaction, providing a qualitative account of the observed oscillations.

1. Introduction

Optical levitation of micrometer-sized particles by laser radiation pressure (RP) was first demonstrated in the early seventies by Ashkin et al. [1,2] in the US, followed by Roosen and Imbert [3] in France. A levitation setup, in simplest form, uses a vertical ($\parallel\hat{\mathbf{z}}$) moderately focused laser beam, a few μm in diameter, and a transparent spherical particle (Fig. 1). Whenever the sphere is large compared to the laser wavelength, the amplitude and action of the radiation pressure force can be obtained from a simple ray-optics picture. Due to the moderate focusing (beam-waist $\omega_0 \gg \lambda$, the laser wavelength), the laser beam may be roughly modeled as a bunch of parallel rays, with a Gaussian repartition in intensity (Fig. 1a). Basically the sphere behaves as a simple lens: an incoming ray, of wave vector $\mathbf{k} = k\,\hat{\mathbf{z}}$ and power dP gets refracted into a ray of wave vector $\mathbf{k}'$, and contributes an elementary force $d\mathbf{F}_{RP} = (\mathbf{k} - \mathbf{k}')dP/c$, neglecting power losses (c is the velocity of light in vacuum). This force is directed towards the center of curvature of the interface, at the refraction point. Consequently the torque around the center of the sphere is null, whatever the ray, and then for the whole beam. The same conclusion holds for reflected rays.

This elementary reasoning is sufficient to find the main trends of the mechanical effects of laser light on the particle. If the refraction index of the particle material is larger than that of the surrounding medium (this is supposed so in Fig. 1), the particle gets stably trapped on the laser axis. A few milliwatts of power yield an axial (levitation) force a few picoNewtons in amplitude. This is much more than the buoyant weight of e.g. a polystyrene microsphere in water, say 3 μm in radius (R). A classical experiment in such conditions is carried out using a very dilute suspension of particles inside a glass cuvette filled with water. A simple method amounts to horizontally shift the cuvette to bring a particle across the laser beam (Fig. 1d). The particle then locks onto the beam axis and starts lifting up. Ascension continues until the particle hits the ceiling of the cuvette (Fig. 1e). There, a 3-dimensional equilibrium is reached, with the particle being locked by the RP force and the contact force exerted

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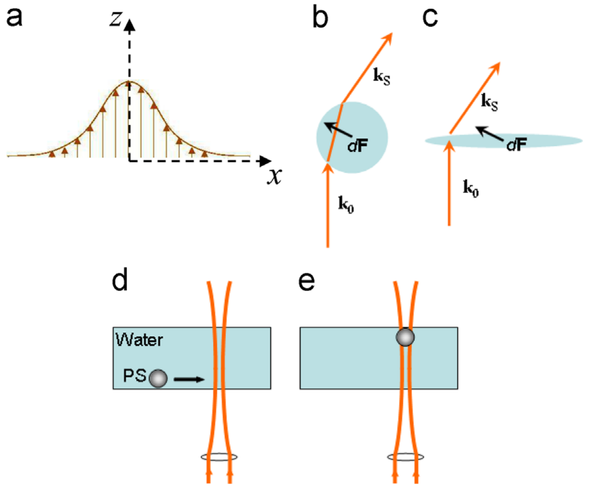

Fig. 1. (a) Ray-optics representation of a low-aperture Gaussian beam. (b, c) A high index transparent sphere behaves as a positive lens. *d***F** is the elementary RP force due to refraction of a single ray. The RP torque applied to a transparent sphere is null. (d, e) Illustration of a simple levitation experiment, with a polystyrene sphere (PS) in water. As the particles are heavier than water, many of them are found lying on the lower boundary of the cuvette (d). The experiment starts by picking up one particle with the laser (we in fact move the cuvette to bring the selected particle on the beam axis). Levitation ends with the particle in contact to the top boundary of the cuvette (e).

by the glass surface. The particle there is kept immobile, in translation and in rotation (Fig. 1e).

Note that static equilibrium may be achieved *in bulk* if the power is lowered such that the RP levitation force just balances the particle weight [2]. A polystyrene spherical particle can be maintained about immobile in such conditions, far from the walls of the cuvette. The corresponding levitation power (P_{lev}) is very small (<3 mW), because of the very small effective weight of a latex particle in water (polystyrene density is only 1.05). The axial equilibrium is not strictly stable, but can be maintained for minutes with about no feedback in power.

Optical levitation, as sketched in Fig. 1, only provides a 2-dimensional (2d) trap. The low aperture laser beam does not provide axial trapping by itself (contrary to optical tweezers). Trapping in 3d based on low-aperture beams can be achieved using a couple of such beams, in coaxial counter propagating configuration [3–6]. Such architectures are much less common than the celebrated optical tweezers (based on a single high-aperture beam), but have the advantage of possibly long-working distances. This advantage is decisive for applications with voluminous samples [6,7].

Having recalled basic principles with spherical particles, we now turn to optical levitation of ellipsoidal particles, the goal of this article. The art of manipulating non-spherical particles with light is a field of growing interest, in colloidal science and biophysics [8], also in view of applications of nanotubes and nanorods in biophysics, microfluidics, microelectronics and photonics [9–12]. The behavior of elongated particles, rods [13–15] or ellipsoids [16–18], has been investigated theoretically, using the Discrete Dipole Approximation (DDA) or the *T*-Matrix method. The mechanical response of an elongated particle to laser light is expectably very different from that of a simple sphere. This indeed is evident from a most naïve model of an elongated particle, in the form of a couple of spheres separated by a fixed center-to-center distance *d* (Fig. 2). Intuition suggests that the composite particle will stably align with its long axis along the beam axis (parallel configuration, hereafter denoted C_0). Stability of the particle pair to small shifts (x, α) around this position can be found using the simple lens analogy, as we did above, now with two rigidly bound lenses (Fig. 2b). Calculations performed in the paraxial approximation lead to the conclusion that C_0 is stable for a confocal pair ($d=2f$), but becomes unstable for larger separations (e.g. $d=3f$), if the laser beam width is larger than the particle size, $\omega_0>R$. Thus the dynamical equilibrium of the particle pair depends on its length and on the beam width. Physically, the main difference with a single sphere is the fact that RP now creates a finite torque Γ on the system, in addition to the force F, and that F and Γ are coupled through x and α.

DDA and *T*-Matrix calculations on true ellipsoids and cylinders show that C_0 is stable with very small particles, but perpendicular configurations have been predicted as well [15]. Experiments with nanoribbons by Pauzauskie et al. [10], small rods [19] and with microdisks [20,21] also indicate that only a dynamical equilibrium may be reached, with the particle constantly oscillating in the laser beam.

Below (Section 2) we report on optical levitation of polystyrene ellipsoids of different aspect ratios (k). As we will see, the above mentioned types of equilibrium are met with the ellipsoids, according to values of k and ω_0. Special attention is paid to sustained particle oscillations, by far the most non-intuitive behavior. The above points, static equilibriums and the existence of oscillating configurations are discussed in Section 3. We will see that a simple ray-optics picture of the laser-ellipsoid interaction indeed reproduces the experimental trends.

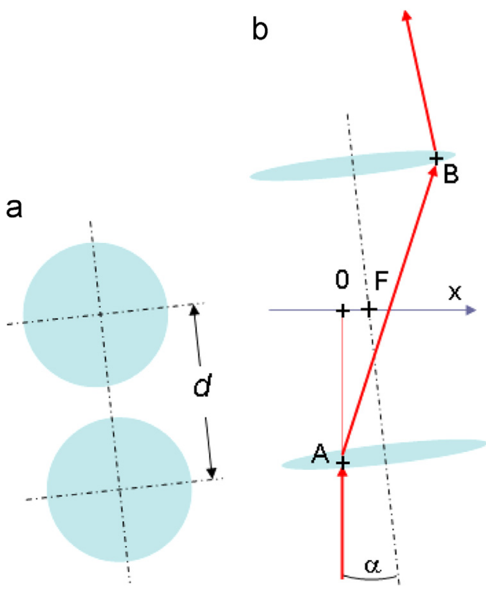

Fig. 2. a doublet of spheres separated by distance d (a) and the 2-lens analogy (b), here for $d=2f$.