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Experimental Results on the Photophoretic Motion and Radiometric Trapping of Particles by Irradiation with Laser Light

S. De Nicola[1], A. Finizo[1], P. Mormile[1], G. Pierattini[1], S. Martellucci[2], J. Quartieri[2], F. Bloisi[3], and L. Vicari[3]

[1] Istituto di Cibernetica C.N.R., Arco Felice, I-80072 Napoli, Italy
[2] Dipartimento di Ingegneria Meccanica, Università Tor Vergata, I-00100 Roma, Italy
[3] Dipartimento di Fisica Nucleare, Struttura della Materia Fisica Applicata, Università di Napoli, I-80125 Napoli, Italy

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Abstract. An experimental observation of the photophoretic motion of micro-sized particles suspended in air has been performed using the radiometric force from a continuous laser beam. The irradiation was used to trap the particles in a confined optical field and to levitate them. Complex photophoretic motion of the particles was observed in the focus of the beam.

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We report some experimental results on acceleration and trapping of micro-sized particles freely suspended in air by the thermal forces from cw visible laser light. Gas suspended particles illuminated by a beam of light of sufficient intensity move along paths which depend on illumination, pressure and composition of the gas, shape and material of the particles. The photophoretic motion is caused by radiometric forces [1–4]. These forces are usually larger than radiation pressure [5], and are due to the uneven temperature distribution over the surface of each particle in the gas. This distribution is caused by the heat produced within the particles by the irradiation.

The reactions of the single surface elements with the surrounding gas result in a net force on the particle. In the experiment we performed, we used particles of carbonized bakelite with $d=2$ µm freely suspended in air contained in a glass cell of 4 mm internal width. A sketch of the basic apparatus is shown in Fig. 1. The TEM mode of an argon laser of beam diameter $w=6$ µm and $\lambda=0.5145$ µm was focused inside the cell

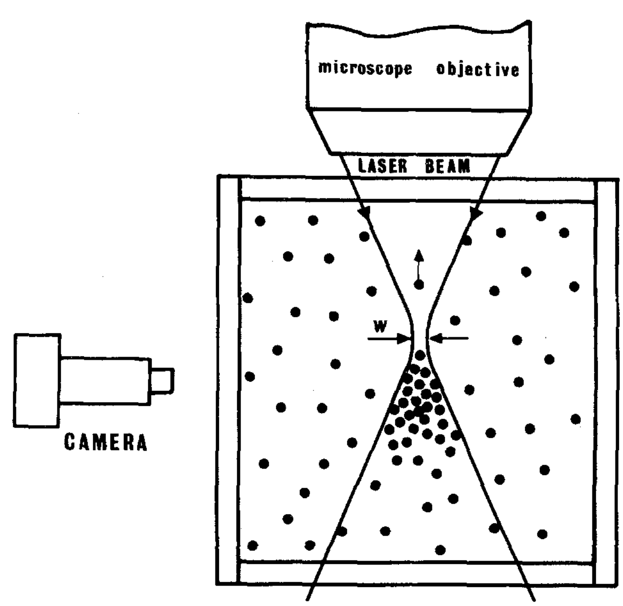


Fig. 1. Experimental setup for observing photophoretic motion in a focused laser beam

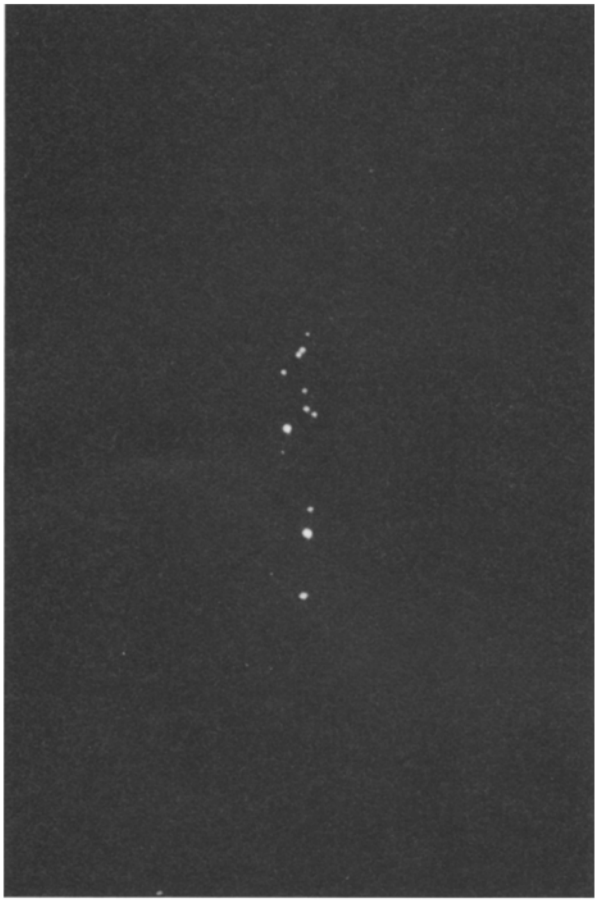
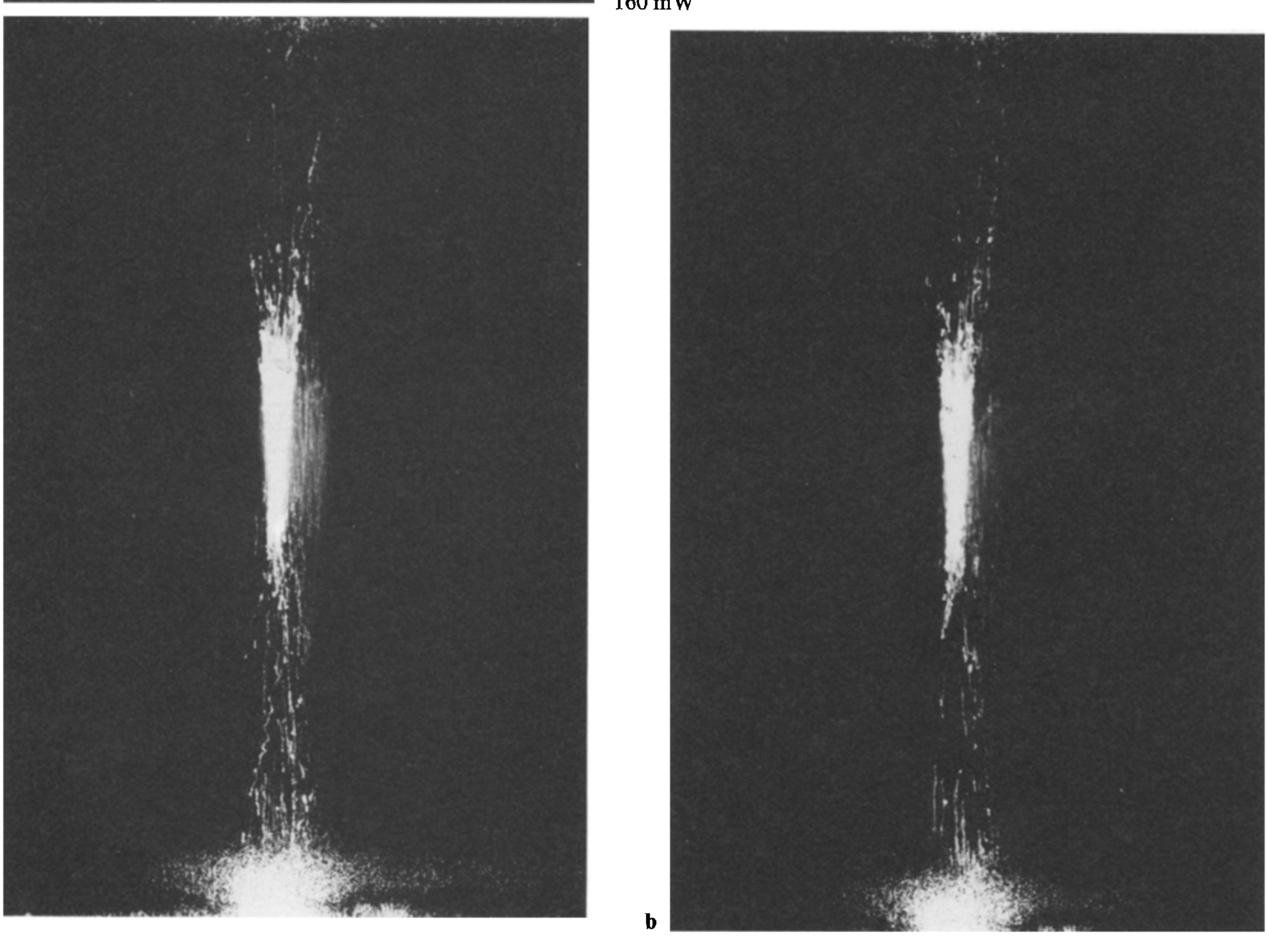


Fig. 2. Radiometrically levitated particles at a beam intensity of 160 mW



a b

Fig. 3a, b. Photographs of photophoretic motions; exposure times: (a) 1/4 s, (b) 1/15 s by a microscope objective. The beam was directed vertically from the top. The resulting motion was observed with a photographic camera. According to the Rubinowitz model [5] a partially absorbing spherical particle concentrates the incident light on the non-illuminated side and moves under the action of the radiometric force upstream towards the light source (negative photophoresis). In our experimental geometry, the particles move against the force of gravity; in Fig. 2 a few particles have been radiometrically levitated at a beam intensity of 160 mW. Increasing the intensity of the light, the particles move until they strike the top surface of the glass cell.

When the beam is interrupted the spheres wander away by Brownian motion. At 200 mW, velocities of $v=1$ cm/s were observed. The collective motion of the particles at such an intensity is shown in Fig. 3. The photographs were taken with an exposure time of 1/4 and 1/15 s, respectively to study the visible paths of the particles and the details of the motion with different time scales. When the particles enter in the area of the focus of the beam, the motion becomes less stable because of the variation of the thermal gradients. We have in fact observed a complex photophoretic motion, a kind of enlarged Brownian motion, with continuous variations in the direction of the particles. When the thermal gradients are such that the net photophoretic force points towards a zone where the beam intensity is less, the particle is expelled from the focal area. Visible in Fig. 3 are the paths of the particles, expelled from the focus, that move upstream towards the light source.

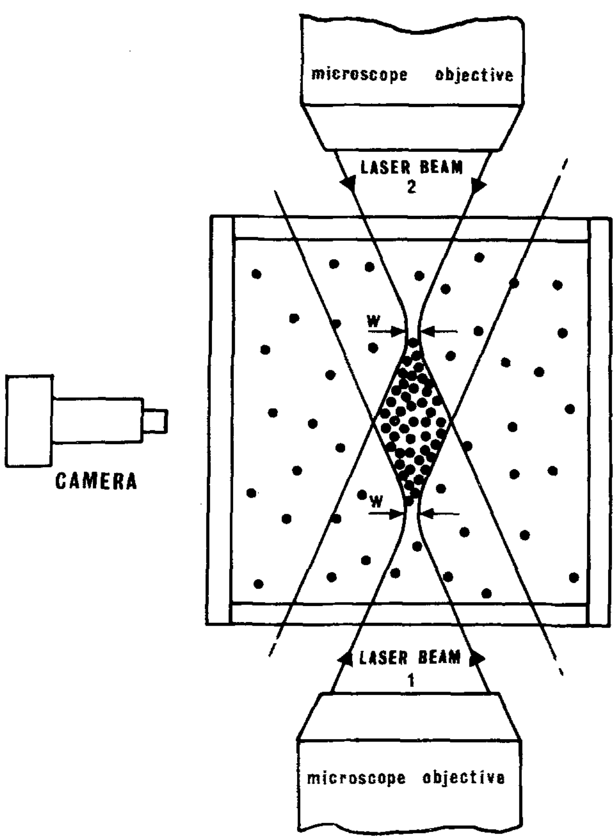


Fig. 4. Sketch of experimental setup for the radiometric trapping of particles

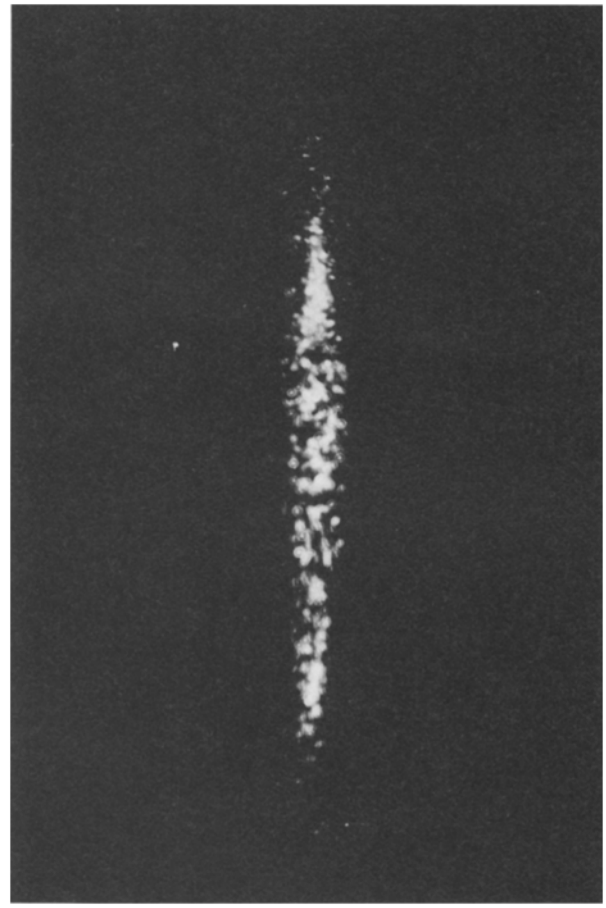


Fig. 5. Trapping of particles. The distance between the foci is 1 mm

To estimate the temperature gradient ΔT needed across a spherical particle in air to account for the observed velocities we can use Hettner's formula [6] for the photophoretic force F

$$F=3\pi R\eta^2 \Delta T/(2MP). \qquad (1)$$

For air $M/R=287.1$ Kg/KJ where M is the molecular weight and R is the gas constant, the viscosity $\eta=182.2\times10^{-6}$ P and $P=1$ atm is the pressure.

From (1) and from Stokes's formula $v=F/3\pi d\eta$, the temperature gradient across the particle is given by:

$$\Delta T=(2/\eta)PdvM/R=0.8\,°\mathrm{C}.$$

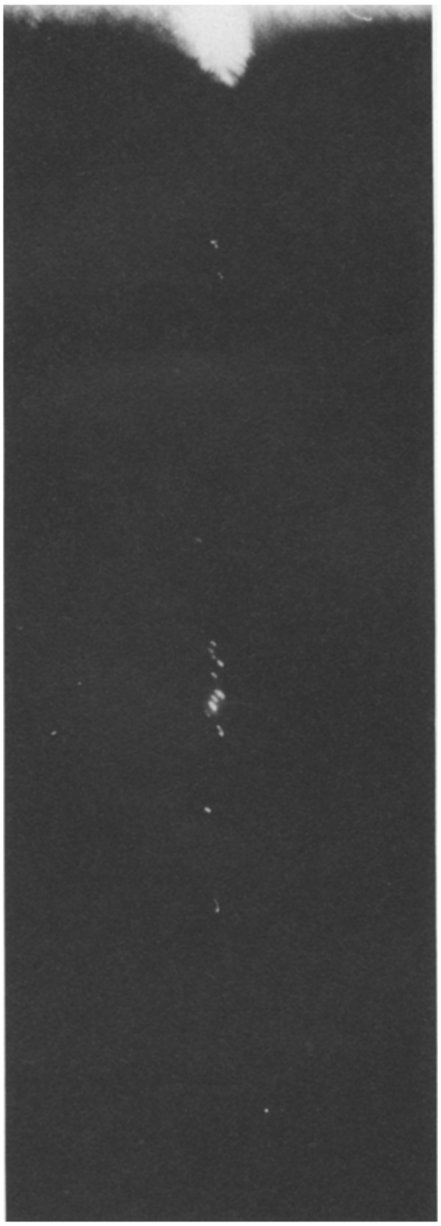


Fig. 6. Trapping of few particles, where the distance between the foci is 0.2 mm

It is clear that Hettner's formula cannot account for the motion of the particles in the focus of the beam. In this case the temperature gradients across the particle depend critically on the position of the sphere in the zone of the focus and the photophoretic force may need a certain time to adjust to another value of local irradiation, i.e. the time to establish a new thermal equilibrium.

This explains the behaviour of symmetric oscillating particles in a further experimental setup in which we utilised two opposed beams, as illustrated in Fig. 4. Due to their random motion the particles enter into the zone of the "optical bottle" of the two beams. A net negative photophoretic force is established after the particle has entered the zone and the particle is induced to move in the plane of symmetry of the double beam.

This effect can be used to trap many particles in a radiometric bottle as shown in the photograph of Fig. 5.

In the experimental situation used for Fig. 5 the oscillations of the particles have been contained in a distance of the order of 1 mm. In Fig. 6 the distance between the foci of the double beam has been reduced to 0.2 mm. In this case few particles have been trapped in the radiometric bottle.

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