Particle motion in a laser beam*

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The motion of particles in beams of powerful laser radiation is a very important and timely problem. It was shown back in 1962[1] that a high-power light beam is capable of strong action on charged and polarizable particles, and the force can reverse sign on going through the resonant frequency of the polarizability. Possibilities were noted of applying this action to prevent particle concentrations from decreasing, to transport particles, and to produce rarefaction or condensation of a medium.

We present here a brief survey of these and of other, stronger and more "dramatic" possibilities of particle motion in laser beam, as a supplement to earlier articles by Ashkin[2] and his popular article translated in the current issue of Uspekhi.

We dwell first on pure electromagnetic action of a high-power light (or radio) beam on a particle. The analysis becomes much simpler if it is assumed that the particle dimension (or the amplitude of its oscillations) is smaller than the wavelength of the light. Then a particle in an electromagnetic field $E(r)e^{i\omega t}$ is acted upon by two forces1) : the gradient force

$$F_\nabla \approx \alpha\nabla (E^2)_{\mathrm{lt}}$$

and the light-pressure force connected with the scattering

$$F_{\mathrm{lt}} \approx (2/3)\, \alpha^2 (E^2/\bar{\lambda}^4)\, \mathbf{n}$$

(at $\bar{\lambda} << a$ we have in the case of a refracting particle $F \sim a^2E^2/4$ and $F_{x\perp} \approx (\pi/2)a^3\partial E^2/\partial x$), where $\alpha(\omega)$ is the polarizability of the particle ($\alpha \approx a^3(\epsilon - \epsilon_0)/(\epsilon + 2\epsilon_0)$ for a quasispherical particle having a dielectric constant ϵ in a medium with a dielectric constant ϵ_0, $\alpha \approx -e^2/m\,(\omega^2-w_r^2)$ for a charged particle with charge e, mass m, and resonant coupling frequency ω_r), and $\bar{\lambda}$ is the reduced wavelength of the radiation. The ratio of the forces is

$$F_\nabla/F_{\mathrm{lt}} \approx \bar{\lambda}^4/\alpha L,$$

where L is the characteristic length of variation of the field intensity. Near a focus, the transverse dimension of the field concentration is usually $L_\perp \approx L_{\parallel}\theta_{\mathrm{foc}}$, where the focusing angle $\theta_{\mathrm{foc}} \approx r/F$ depends on the initial radius r of the beam and on the focal length of the lens F. In the case of a single-mode laser we usually have $L_\perp \sim \lambda$, $\theta \sim \lambda/L_\perp$, and $L_\parallel \sim L^2_\perp/\lambda$, i.e., on the order of the Fresnel length. In the case $L_\perp \sim \lambda$ we obtain $F_\nabla/F_{\mathrm{lt}} \approx (\bar{\lambda}/a)^3(\lambda/L) \gg 1$ at $\alpha \approx a^3$; $\bar{\lambda} >> a$, i.e., the gradient force can exceed the light-pressure force.

It is easy to obtain from the foregoing expressions all the possible behaviors of the particle in the beam: drawing in of a particle with $\epsilon_1 > \epsilon$ into a beam and then its repulsion at $\epsilon_1 < \epsilon$. This case $\bar{\lambda} >> \mathbf{a}$ includes the forces exerted by the light on atoms whose dimensions are smaller by three orders of magnitude than the wavelength of the light. (This is exactly why the case $\bar{\lambda} \gg \mathbf{a}$ was paid particular attention in [1].)

In the case of a small field gradient, sufficiently large particle dimensions, or large polarizabilities, the light pressure can exceed the gradient force. Given the force acting on the particles in the medium, the particle motion is determined in the case of small forces by equating the electromagnetic force to the Stokes force $F \sim 2\pi\eta a u$, and at large forces by equating it to the gasdynamic-pressure force $F \approx \pi a^2\beta_\rho u^2$, where u is the particle velocity, β the particle form factor, and ρ the density of the medium. For example, $u \approx E(4\pi\beta_\rho)^{1/2}$ at $F \approx a^2E^2/4$. This means that, say, at $E \sim 10^5$ cgs esu, corresponding to focused power on the order of hundreds of megawatts, we obtain $u \approx 3 \times 10^4 - 10^5$ cm/sec, i.e., the velocity of the light-scattering particle approaches the sound velocity, and this should become manifest in a change of the scattered-light spectrum.

A very high gradient force can be used to accelerate particles to high velocities[4]. The great progress in the production of very powerful light pulses with very short durations and rise times makes it possible to apply to an electron in a laser focus a gradient force equal to

$$E_{\mathrm{eff}} \approx (e/2m\omega^2)\, E_0^2/L \sim 1-10\ \mathrm{MW/cm}.$$

When the focus moves in synchronism with the accelerated particles, it is possible to obtain ultrarelativistic electrons with energies many times larger than the oscillation energy[4].

We consider now the forces connected with the absorption of light. Three types of forces can be produced: by heating and motion of the medium itself (convection dragging), heating of the medium by the absorbing surface of the particle (radiometric pressure), and pressure due to evaporation of the particle itself (light-reaction pressure[5]). We note that all these effects can greatly exceed the light pressure in the case of appreciable absorption, and can be observed in experiment with high probability. For example, the light-reaction pressure[5] is

$$p_{\mathrm{react}} \sim \dot{M}v_{\mathrm{out}} \sim Iv/[\lambda + (1/2)\, v^2] \approx (p_{\mathrm{lt}}cv)/[\lambda + (1/2)\, v^2],$$

where λ is the specific heat of the evaporation, v_{out} is the outflow velocity of the vapor of the material, and $I \approx p_{\mathrm{lt}}c$ is the flux density of the light energy, i.e.,

$$p_{\mathrm{react}}/p_{\mathrm{lt}} \approx cv/[\lambda + (1/2)\, v^2] \sim cv/\lambda \sim 10^4.$$

In this case the light-reaction pressure can reach 10^{12} atm. This pressure can be used, in particular, to accelerate macroscopic particles [5, 6] to $10^6 - 10^8$ cm/sec, to obtain artificial micrometeorites, to produce particles that release locally large energy concentrations when colliding with a target or with one another. Proposals have been advanced recently to use high-power cw gasdynamic lasers to change satellite trajectories.

At moderate light-flux densities, an important role in radiometric effects with transparent particles may be assumed by the so-called "surface" absorption of light (although the fraction of light absorbed by the surface is small, the absorbed energy is released in a very narrow layer and can result in very large overheating). The focusing role to the particle itself is important. In the case of absorbing particles, their motion in beams of powerful light is connected entirely with the radiometric and reactive forces[7]. This problem is quite interesting in connection with the passage of beams of powerful gas lasers through fog, haze, or clouds[7].

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*Comments on the article " The Pressure of Laser Light", by Arthur Ashkin, a translation of which was published in the current Russian issue of Uspekhi Fizicheskikh Nauk [110, 101 (1973)]

1) The use of these forces to accelerate particles in radio waves was the subject of the articles in [3].

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