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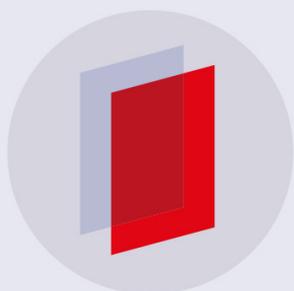
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Letters and comments

A new radiation pressure formula to calculate the optical force exerted by a laser on a trapped particle

Abstract. This letter proposes a new expression of the radiation pressure force exerted by light on any piece of matter. This expression defines the optical force on any macroscopic particle surrounded by an isotropic fluid. It is restricted to quasi-permanent light illumination of the scatterer, where the usual tensors of Minkovsky and Abraham become equivalent. As experimental and numerical aspects of this approach were previously developed, I focus here on the derivation of this new formula from Maxwell theory.

Résumé. Cette lettre propose une nouvelle expression de la force de pression de radiation exercée par la lumière sur la matière. Cette expression définit la force optique exercée sur toute particule macroscopique entourée d'un fluide isotrope. Elle concerne un éclairage quasi-permanent de l'objet diffusant, où les tenseurs habituels de Minkovsky et Abraham deviennent équivalents. Puisque les aspects expérimentaux et numériques de cette approche ont déjà été développés, je présente ici comment cette nouvelle formule découle de la théorie de Maxwell.

The use of two upward laser beams, whose distance can be precisely tuned on a $40\ \mu\text{m}$, range, enabled us to obtain the first experimental optical forces exerted by a beam on an excentred latex sphere having a radius bigger than the beam one [1, 2]. This method is used first to validate a numerical approach of the problem [2, 3], second to begin applications in the phospholipid deformability field [4]. The numerical method we used [3] is specific to the interaction of a Gaussian beam with a micron-sized sphere. I present here a more general expression of this radiation pressure force with the only hypothesis that the electromagnetic field is in a permanent regime near the scatterer.

The forces exerted on matter by light are unambiguous when this matter is surrounded by vacuum. We just have to know the electromagnetic field pattern in a fixed volume V , enclosing this piece of matter, to calculate the radiation pressure force:

$$F = \int_{\Sigma} [S] d\Sigma - \frac{\partial}{\partial t} \int_V \epsilon_0 E \wedge B dV \quad (1)$$

where $[S]$ is the stress tensor applied on the surface Σ that limits the volume V . We can choose for example the Minkovsky form:

$$S_{ik} = -E_i D_k - H_i B_k + \frac{1}{2} \delta_{ik} (E \cdot D + H \cdot B) \quad (2)$$

As soon as a fluid of refractive index $n(n^2 = \epsilon/\epsilon_0)$ is present around the object, the force exerted on that

object is more difficult to define in general since the light is acting on the object and also on the fluid because of the light energy density gradients.

However, when the light inside V is in a permanent regime, the second integral of (1) (which is responsible for the difference between Minkovsky and Abraham forces) vanishes. In that case, Gordon obtained a very synthetic expression of the force F exerted on the object [5, equations (3.6) and (3.11)]:

$$F = - \frac{d}{dt} \int_{V_{\text{ext}}} \epsilon E \wedge B dV_{\text{ext}} \quad (3)$$

where V_{ext} is the volume exterior to the surface Σ . This expression supposes that the volume V_{ext} is filled with the fluid and that $V + V_{\text{ext}}$ contains the entire electromagnetic field. F represents here the opposite of the rate of change of the pseudo-momentum of the light because of the presence of the object (as this change occurs only in V_{ext}).

Equation (3) is easy to use when a light pulse is acting on a piece of matter. In that case, it is easy to define a surface Σ surrounding the object but included in the total electromagnetic field, and a volume V_{ext} containing all the light around Σ . Now, optical levitation experiments usually correspond to a continuous illumination of the scatterer. Then, the following scenario will enable us to adapt (3) to that situation, where the volume V_{ext} is infinite:

- Imagine that a piece of matter is included at the time $t = 0$ in the centre of a volume V where a permanent electromagnetic field E_i, B_i is already present. Before $t = 0$, the light is in a permanent regime everywhere and no matter is present. Equation (3) implies then:

$$F(t < 0) = - \frac{d}{dt} \int_{V_{\text{ext}}} \epsilon E_i \wedge B_i dV_{\text{ext}} = 0. \quad (4)$$

- After $t = 0$, a scattered wave is spreading from the object. Here, Σ is chosen at the position attained by the scattered wave a time $t > 0$. Using equation (3), the force F can then be calculated during the following time dt . During that time dt , the field varies only in a thin shell covering Σ where the source field is replaced by the total field (the thickness of that shell is $c_{\text{sca}} dt$, where c_{sca} is the speed of the scattered wavefront). This slight change of the field pattern in V_{ext} (compared to equation 4 case) leads to:

$$F = - \frac{d}{dt} \int_{V_{\text{ext}}} \epsilon E \wedge B dV_{\text{ext}} = \int_{\Sigma} (\epsilon E_i \wedge B_i - \epsilon E \wedge B) c_{\text{sca}} \cdot d\Sigma. \quad (5)$$

This result is applicable for any source field in interaction with any piece of matter surrounded by a fluid medium and with the only hypothesis that the field is locally in a permanent regime near the studied object. It generalizes the theoretical expression used in [2, 3] where $\epsilon \mathbf{E}_i \wedge \mathbf{B}_i - \epsilon \mathbf{E} \wedge \mathbf{B}$, \mathbf{c}_{sca} and $d\Sigma$ are supposed colinear to the radius coming from the centre of the scatterer (since the surface Σ is chosen vary far from that scatterer).

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