Shedding light on the concept of light pressure

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Abstract

The idea of light pressure has fascinated scientists, since it was first proposed by Maxwell in the late 19th century. Numerous theoretical and experimental works involving optical forces have been carried out to characterize the radiation pressure of light in media, although the issue remains extensively debatable. The present article aims to explicate the feature of this intricate optical phenomenon.

Keywords: Light pressure, Light momentum, Radiation optics.

Resumen

La idea de una presión en la luz ha fascinado a los científicos desde que fue propuesto por primera vez por Maxwell, en el siglo XIX. Numerosos trabajos teóricos y experimentales que involucran fuerzas ópticas, se han llevado a cabo para caracterizar la presión de la radiación de la luz en los medios de comunicación, aunque la cuestión sigue siendo ampliamente discutible. El presente artículo tiene como objetivo explicar la característica de este fenómeno óptico intrincada.

Palabras clave: Presión de la luz, Impulso de luz, Óptica de radiación.

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I. INTRODUCTION

Arthur Clarke, a science fiction writer, mentioned the running of solar sails by the light pressure, in his 1972 story: *The Wind from the Sun*. Light (or radiation) pressure is no longer the realm of science fiction, but science fact. The theoretical treatment of light pressure in Quantum Optics now can be evidenced experimentally, particularly with the availability of highly intense laser beams, which are capable of producing robust results. For example, the pressure of light can significantly change the length of a Fabry-Perot resonator to cause optical bistability [1]. Ashkin –about 25 years ago– predicted a number of light-pressure-based applications [2].

Therefore, this shining force has come out of the cupboard to mean a revolution in optical manipulation [3]. The appearance of new terms, such as “optical trapping”, “optical binding”, “optical tweezers”, and “optical acutators” are paradigmatic examples in the increasingly important subject of nanotechnology. A newer emerging term in this context, is the “laser microfluidics or optofluidics” [4]. Therefore, the aim here is to familiarize to the nonprofessionals with the preliminary concept of light pressure.

II. THE CONCEPT

Many generations have passed through the great halls of science, since Maxwell envisaged the potential forces of pressure of electromagnetic waves, in his celebrated work: *Treatise on Electricity and Magnetism.* In 1871, Maxwell stated that: “In a medium in which waves are propagated, there is a pressure in the direction normal to the wave, and numerically equal to the energy contained in unit of volume”.

He believed that the pressure of light is measurable based on the fact that since light has electromagnetic momentum, it should then have mechanical momentum too. If light reflects, the momentum would then be twice, and so the light pressure would also be twice. Maxwell yielded the light pressure value of 4.7×10^{-6} N/m^2, which is quite small, and hence considered negligible in any optical experimentation.

About two decades later, Lorentz [5] advanced Maxwell’s electromagnetic theory in Quantum Optics more analytically by introducing Lorentz transformation. Lepedew [6] was first to report the light pressure value of $3.08 \times 10^{-5} \pm 1.7 \times 10^{-6}$ dyn/cm^2 (1 dyn/cm^2 = 0.1 N/m^2) experimentally, in 1901, through a complicated setup of ideally absorbing and reflecting surfaces. In addition, Nichols and Hull [7, 8] made a vigorous attempt to measure the pressure of light in the same year. They had the most accurate radiometer in the world and a state of the art laboratory at their disposal and therefore came up with the most accurate measurement ever recorded, of being just 10% deviated from that of Maxwell's value (4.7×10^{-6} N/m^2). These experimental confirmations concerning Maxwell's prediction were indeed a great step forward to the realization of light pressure.

Shortly, the theoretical side of the effect was more substantiated by –for example– Poynting [9], in 1905, who presented a detailed geometrical calculation of the force driven by the light incident, from free space onto a transparent and non-dispersive dielectric medium. Assuming an outward force normal to the surface of the dielectric opposite to the direction of propagation of the incident electromagnetic field.

This implied that the effects of light pressure exerted on a dielectric surface, could be regarded as the transfer of momentum, from photons at the surface parallel to the propagation of the incident electromagnetic radiation.

Nevertheless, the recent impetus in the subject was driven by Ashkin and Dziedzic classical experiment [10], in 1973 with the following feature:

They focused a pulsed laser beam on the free surface of pure water. As a result, they observed formation of a bulge on the water surface at the point of entry of the focused laser beam, as depicted in Figure 1.

A time resolution of 10 nsec has made it possible to observe the time variation of the focal length, of the induced lens, which took 400 nsec to develop fully. The flat water surface was lifted towards the beam to a height on the order of a micrometer, and had its focal length reaching values of about 0.01 cm, at the instant of the maximum pulse power.

The elevation of the water surface was inversely proportional to the water surface tension, which maintained a tension balance between the Laplace force of the bulged surface and the light pressure. As is known, the Laplace equilibrium condition for a curved surface that separates two different media is [11]:

$$\gamma\left(\frac{1}{r_1}+\frac{1}{r_2}\right)=\Delta\rho g z, \tag{1}$$

where γ is the interfacial tension of the two media in contact, and r_1 and r_2 are the principal curvature radio of the surface, at a point of z coordinate, g is the gravitational constant, and $\Delta\rho = \rho_1 - \rho_2$ of ρ_1 and ρ_2 being the densities of the two media.

When there is no deformation of the surface, both r_1 and r_2 are infinitely large, making $\Delta\rho g z$ to tend to zero.

The photomechanism of the force responsible for the bulge was ascribed to the increase of the photon momentum, from its free-space value of $\hbar\omega/c$ to Minkowski's value of $n\hbar\omega/c$, for light of frequency ω in a medium of refractive index n (Minkowski's expression is explained in the next section).

Thermal and volume nonlinear optical effects were negligibly small under Ashkin and Dziedzic's experimental condition.

Generally, the laser-induced liquid surface deformation can theoretically be derived under the periodical modulation of the laser light pressure [12], but the results cannot be very accurate because we also need to consider the laser-induced thermal effect, even in the case of non-photoabsobing liquids, such as pure water. However, by using the nanometric precision imaging method of digital holographic microscopy, the issue of thermal effect can practically be resolved [13].

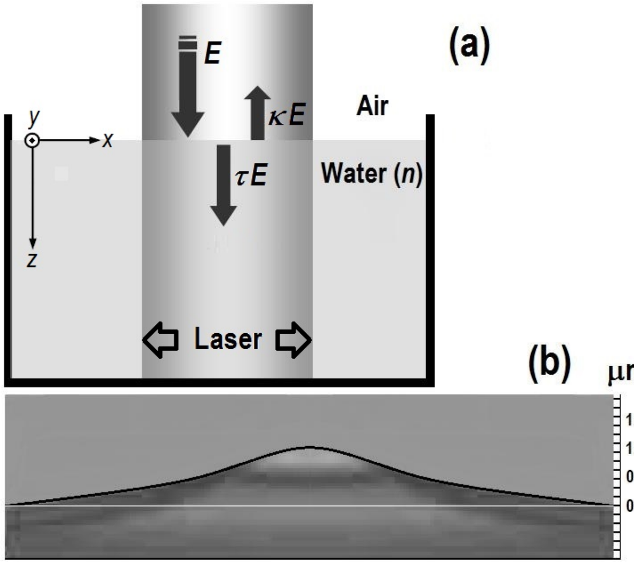

FIGURE 1. (a) Reflection and transmission coefficients (for E_x, E_y) are κ and τ, respectively. The radius of the beam waist located at the water surface is about 4.5 µm. (b) A graphic representation showing an outward bulge of the order of 1 µm. The reason for the low value of the bulging effect is the large surface tension of water.

Meanwhile, for better determination of a static surface property, a stable high-power continuous wave laser is preferred to a pulse laser. Primarily, a relatively low power laser beam can probe the water-air boundary of the water surface by total internal reflection, as shown in Figure 2.

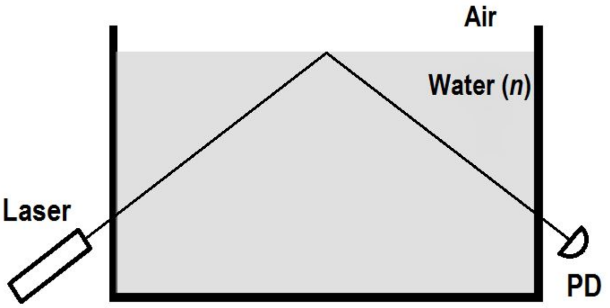

FIGURE 2. For the water-air interface probe by a photo-detector (PD) the angle of incidence > 48.6º (the critical angle) should be considered.

On the character of light pressure (Figure 1), the constant liquid surface deformation under continuous wave laser beam gives the static value, while the frequency response spectrum of the deformation under modulated excitation gives the dynamic value. Different liquids of different surface tensions can be used for the light pressure-induced bulging effect test.

For example, the surface tension of water at 20°C is more than six times that of perfluorohexane, at the same temperature. The relationship between surface deformation and other important surface properties, such as surface tension and viscosity, has been derived against laser irradiation [14].

III. THE RIVAL OPINIONS

While the momentum of light is well definable in free space, it is unfortunately not so in a medium, i.e., except in vacuum, electromagnetic momentum by itself is an intrinsically ambiguous notion. For example, when light passes through a medium it exerts forces on the charges, setting them in motion, and delivering momentum to the medium. Since this is associated with the wave, it is not unreasonable to include some or all of it in the electromagnetic momentum, even though it is purely mechanical in nature. But figuring out exactly how and where this momentum is located can be very tricky.

Down the history, in formulating optical momentum in media, the first expression was proposed by Minkowski [15] in 1908. He calculated that the momentum density of an electromagnetic wave propagating in a dielectric medium, should increase relative to its free-space value by a factor equal to the refractive index of the medium *n*, representing the additional momentum being carried by the polarization of the medium. That is,

$$P_{\text{photon}} = \frac{n\left({}^{h}/_{2\pi}\right)\omega}{c}, \tag{2}$$

where $h/2\pi$ is the reduced Planck constant or Dirac constant $\hbar$, ω is the light angular frequency (2π times the frequency), and c is the light speed.

On the other hand, Abraham [16] in 1909 came up with a quite opposite expression for the momentum density, suggesting that it should instead decrease by the factor of n (and transferring a fraction $(n - 1)/n$ of its momentum to the medium). That is,

$$P_{\text{photon}} = \frac{\left({}^{h}/_{2\pi}\right)\omega}{cn}, \tag{3}$$

These contradictory tensor expressions gave rise to what is frequently referred to as the Abraham-Minkowski controversy, which has been debated extensively by a number of researchers for the last century. In fact, the literature on the light pressure has been dominated that which of the two momentum-energy tensor expressions can serve the best in modeling the phenomenon. Although some recent researchers have made attempts to bring about a reconciliation between the two expressions, by identifying the Abraham momentum as the kinetic momentum, and the Minkowski momentum as the canonical momentum as, for example, in refs. [17, 18], although emphasis has been made that, all relevant forces should carefully be considered in the unification treatment.

This implies that the resolution of the Abraham-Minkowski controversy lies in the realization that electromagnetism recognizes two distinct momenta, the kinetic momentum as being responsible for the overall center of mass translations of a medium, and the canonical momentum as being responsible for translations within or with respect to a medium. The total momentum is of course conserved, whichever momentum we use for the light. Yet, it has been shown [19] that Abraham's formalism about the photon momentum acting in a medium is not compatible with the momentum, and energy conservation laws since Abraham believed that energy conservation requires a fundamental modification of Lorentz's electron model to include supplemental internal, non-electromagnetic source of energy, and hence the light pressure theory should be frame-dependent. Minkowsky's expression instead seems to be more plausible by holding to the Maxwell-like formalism [20], and in accordance with the third Newton law there is a counterpart of the force applied to the light wave that increases its momentum.

As yet, the theory of light pressure is an exoteric one in the realm of Quantum Physics that has brought up paradoxes, such as that of Einstein-Podolsky-Rosen (known by their initials as EPR) [21], which is in essence similar to the well-known paradox of Schrödinger's cat. Perhaps, Einstein was right that Quantum Physics is distanced from the elements of reality due to being incomplete relative to Classical Physics that has twice as many dynamical variables that can be known with arbitrary precision, but half of this information is missing in Quantum Physics, making it to an overwhelming extent statistical.

IV. CONCLUSIONS

Experimental evidence of light pressure is certainly strong, as it was reviewed here, but it has a theoretical fillip side.

Relying on the quantum approach for interpretation, one may face different perspectives, which gives rise to the points of interpretive controversy like the case of light pressure.

Therefore, an ideal judgment appears to be not so convenient as far as the light induction landscape is concerned (an important note regarding the use of right mathematical approach is given in the Appendix).

On the other hand, if we desire to study the exact form of the light mechanical force field on a medium, we need to deal with the utmost care because we are practically dealing with a quite small force in the range of piconewtons that could make precise detections erroneous.

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APPENDIX

It is important to note that some introductory physics texts for providing the reason that light exerts pressure on matter, consider the force exerted by an electromagnetic wave on an electron, which is "mathematically incorrect". This is also what two eminent physicists, Tony Rothman from the Princeton University (USA) and Stephen Boughn from the Haverford College (USA), have warned about in the abstract of their joint article, *The Lorentz force and the radiation pressure of light.* The aforementioned authors give the notorious example of the textbook by Paul Tipler and Gene Mosca, *Physics for Scientists and Engineers* Vol. 2, 5th Ed. (W. H. Freeman, New York, 2004), and conclude:

> *"… the explanations presented in textbooks and in the classroom are so seriously flawed that even students sometimes notice the difficulties. Rather than try to paper over these problems with what must be regarded as nonsensical arguments, the occasion would be better exploited to point out that physics is composed of a collection of models that are brought to bear in explaining physical phenomena, but that these models have limited domains of applicability and, as often as not, are inconsistent".*