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Physicists make first observation of the pushing pressure of light

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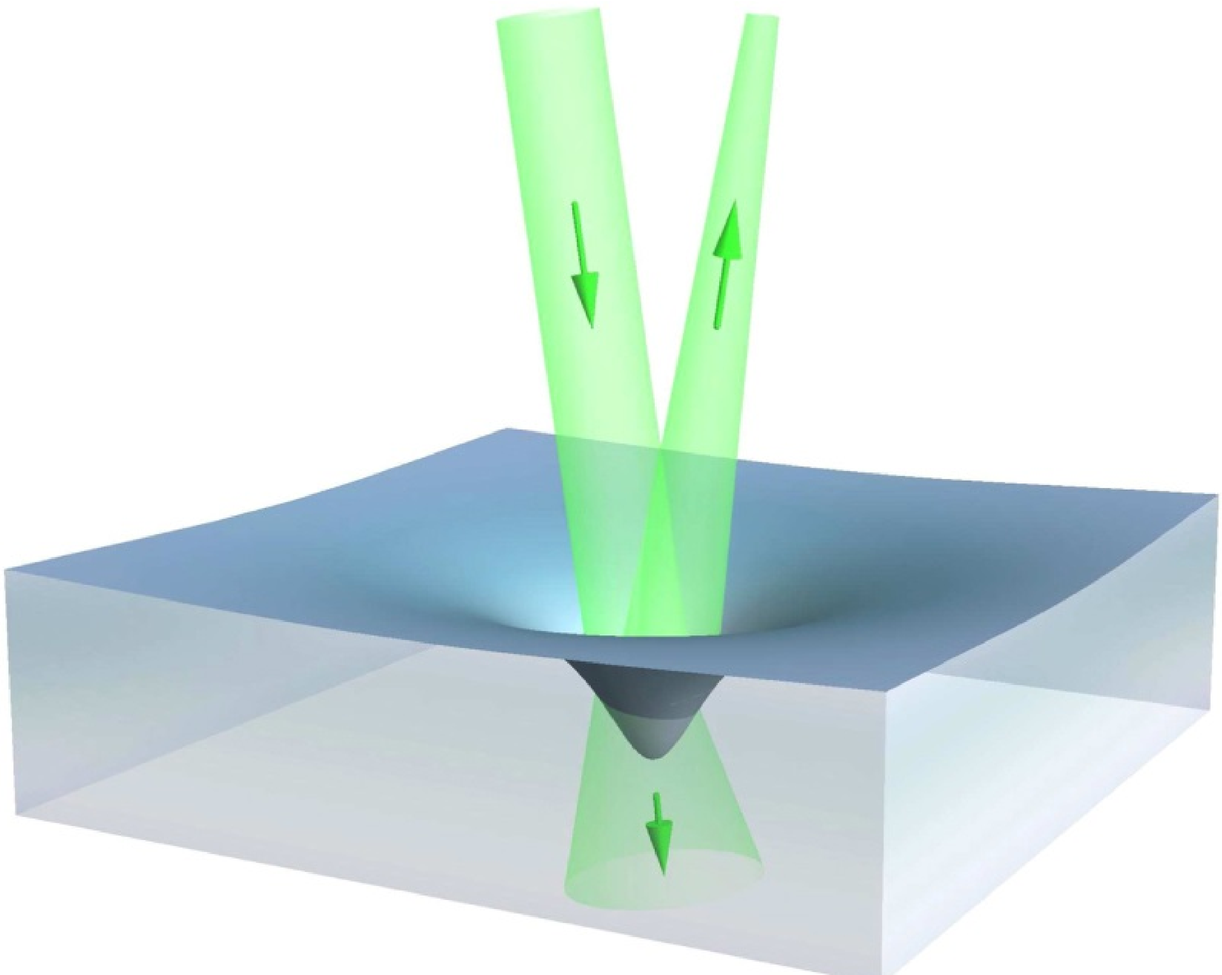


When light impinges on the surface of a liquid, part of the light is reflected and the remaining fraction is transmitted. The new experiments show for the first time that the liquid surface bends inward, meaning that the light is pushing on the fluid in agreement with the Abraham momentum of light. Credit: Zhang, et al.

(Phys.org)—For more than 100 years, scientists have debated the question: when light travels through a medium such as oil or water, does it pull or push on the medium? While most experiments have found that light exerts a pulling pressure, in a new paper physicists have, for the first time, found evidence that light exerts a pushing pressure.

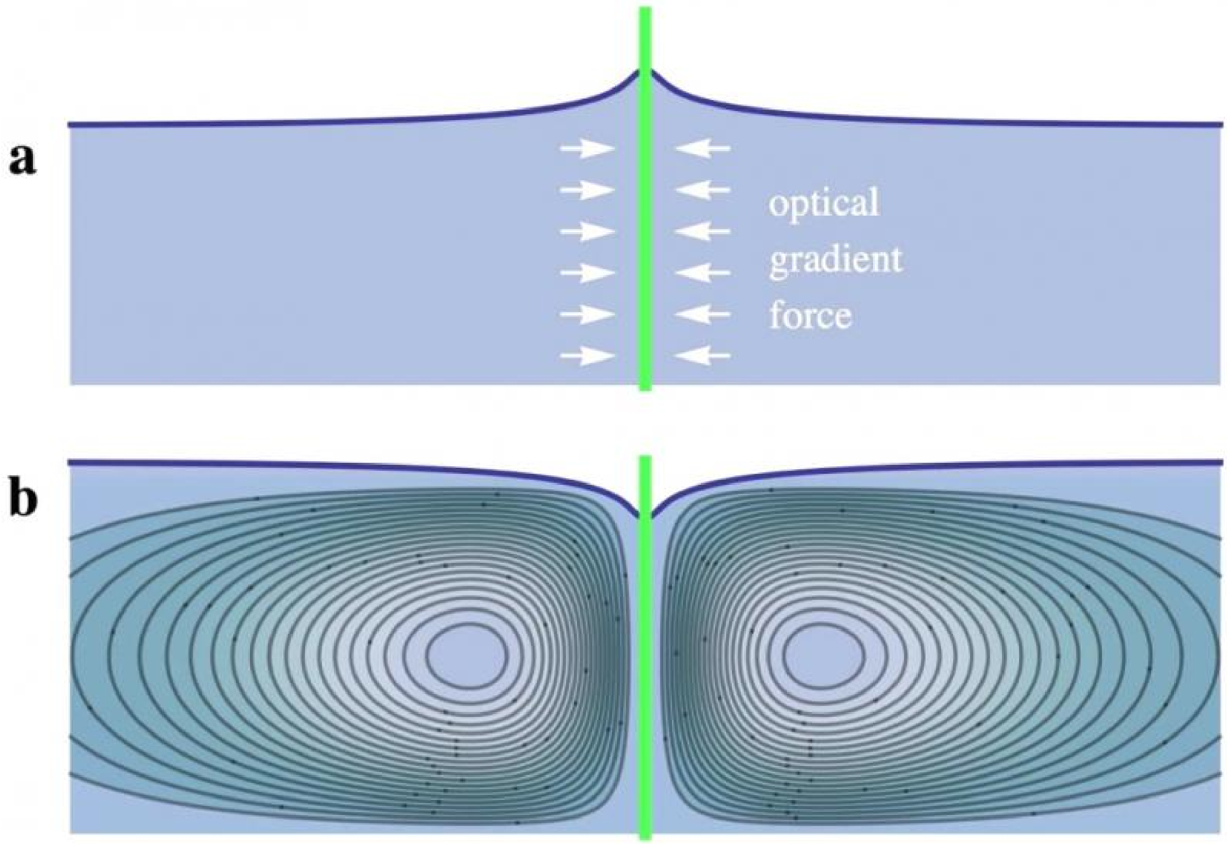
The scientists suggest that this apparent contradiction is not a fundamental one, but can be explained by the interplay between the light and the fluid medium: if the light can put the fluid in motion, it exerts a pushing force; if not, it exerts a pulling force.

The researchers, Li Zhang, Weilong She, and Nan Peng at Sun Yat-Sen University in Guangzhou, China, and Ulf Leonhardt at the Weizmann Institute of Science in Rehovot, Israel, have published a paper on the first evidence for the pushing pressure of light in a recent issue of the *New Journal of Physics*.

Minkowski vs. Abraham

The debate on the nature of the pressure, or momentum, of light goes back to 1908, when Hermann Minkowski (best known for developing the four-dimensional "Minkowski spacetime" used in Einstein's theory of relativity) predicted a pulling force. In 1909, physicist Max Abraham predicted the exact opposite, that light exerts a pushing force.

"Scientists have argued for more than a century about the momentum of light in materials," Leonhardt told *Phys.org*. "Is it Abraham's, is it Minkowski's? We discovered that momentum is not a fundamental quantity, but it is made in the interplay between light and matter, and it depends on the ability of the light to move the material. If the medium does not move, it is Minkowski's, and if it moves, Abraham's. This was not understood before."



(a) Minkowski's momentum of light: the surface bulges out, indicating that light is pulling on the medium. This regime occurs when the light is not able to put the fluid in motion (the light is too focused or the container of fluid too shallow). (b) Abraham's momentum of light: the surface bends inward, indicating a pushing force. This regime occurs when the light is able to move the fluid. In both figures, the surface deformations are exaggerated for making them visible. Credit: Zhang, et al.

The two different types of pressures can be experimentally distinguished by illuminating the surface of a liquid with a light beam and seeing whether the liquid rises or falls. If the liquid's surface bulges out, then the light is pulling the liquid in agreement with Minkowski's theory. If the surface bends inward, the light is pushing in agreement with Abraham's theory. While the predictions of the two theories agree in empty space (which has a refractive index of 1), they differ in any medium with a refractive index greater than 1.

In the new study, the scientists showed that they could make the surface bend inward, corresponding to the pushing pressure, by using a relatively wide light beam and a relatively large container—two factors that cause the light to create a flow pattern in the fluid. The researchers demonstrated this pushing force in both water and oil, which have different refractive indices, in agreement with Abraham's theory.

In previous experiments, which found that light exhibits a pulling pressure, researchers had used narrower light beams and smaller containers than those in the current experiment, so the researchers here modified their original experiment by using a narrower beam. Their results in this new regime now revealed a pulling pressure, in agreement with the experiments from previous studies, suggesting that the nature of the pressure depends not only on the light, but on the fluid as well.

Light and snooker balls

Taking a step back, we might ask, why does light have momentum in the first place? Leonhardt explains that the momentum of light is slightly different than its energy, and can be understood as a pressure that causes motion, in analogy to snooker (i.e., billiards) balls.

The momentum of light (along with the solar wind) creates the tails of comets by pushing material off the comets. Credit: European Southern Observatory

"Imagine a snooker game," he explained. "The player kicks one ball and this ball kicks another one. In all these kicks, the momentum the player initially gives to the cue stick is setting things in motion. Light may kick materials as well, just like the snooker balls, but these kicks are minuscule. In some circumstances, however, the kicks of light make a dramatic appearance. One example is the tail of a comet. Johannes Kepler speculated a long time ago that comet tails are caused by light pushing material off the comets, because they always point away from the Sun; we know now that he was partly right (the rest of the pushing is done by the solar wind). The ability of setting mechanical objects into motion is called momentum. It is not the same as energy, but often closely related to it."

He went on to explain that the controversy of the pushing vs. pulling nature of light's momentum only concerns situations in which light is not completely reflected off an object, but at least partially transmitted through the material.

"There is no conceptual problem with the momentum of light if the light is reflected, for example from a mirror or the dust particles of a comet, because here the momentum balance is very simple: twice the incident momentum causes motion, the incident and the reflected one," Leonhardt said. "If, however, part of the light is transmitted, then the transmitted light in the material needs to be taken into account. There it matters whether the Abraham or Minkowski momentum is carried by the transmitted light, as it affects the net balance of momentum, whether it is positive or negative. In Abraham's case the net balance leads to a push, in Minkowski's to a pull."

The findings have both fundamental and practical significance. Fundamentally, the results help scientists gain a better understanding of the nature of light. While it has long been known that light carries both energy and momentum, and that the energy of a photon is quantified by its frequency f times Planck's constant h, the momentum of light has not been so easy to describe. Does the momentum increase or decrease as the refractive index of the medium increases? The results here suggest that the answer depends on whether or not the light can put the fluid into motion: if it can, its momentum decreases and it exerts Abraham's pushing force; otherwise, its momentum increases and it exerts Minkowski's pulling force.

This distinction may prove very useful, as scientists have recently begun to develop applications that take advantage of light's momentum, or pressure. One such application, called inertial confinement fusion, uses the power of light's momentum to ignite nuclear fusion. Physicists can also use the momentum exchange between light and an oscillating mirror to cool the mirror to its quantum-mechanical ground state. Optical manipulation techniques, such as optical tweezers, use the gentle pressure of light to hold and manipulate cells for biomedical and nanoengineering applications. The researchers here hope that a better understanding of the momentum of light will contribute to these developments.

More information: Li Zhang, et al. "Experimental evidence for Abraham pressure of light." *New Journal of Physics*. DOI: 10.1088/1367-2630/17/5/053035

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