PUSHING, PULLING, TWISTING, STRETCHING: THE POWER OF LIGHT UNDER THE MICROSCOPE

By Dr Philip H. Jones

Of the many uses we have for light such as illumination or digital communication, perhaps the most surprising is physical manipulation of matter. Holding and moving objects without touching them may seem like the stuff of science fiction, but a profound understanding of the interaction between light and matter can make this a reality, at least on the microscopic scale. Since its invention, the technique of 'optical trapping' has evolved into a tool with applications beyond the narrow scope of physics, and in particular, has enabled remarkable discoveries in biology and medicine.

The first realisation that light can exert a force on matter is sometimes traced back to Johannes Kepler (1571-1630) who explained the appearance of the tails of comets thus:

> The direct rays of the Sun strike upon it [the comet], penetrate its substance, draw away with them a portion of this matter, and issue thence to form the track of light we call the tail […] In this manner the comet is consumed by breathing out is own tail.

It is perhaps fanciful to attribute to Kepler knowledge of what we would now call *radiation pressure* or the pushing effect of a light wave, since the necessary theory of electromagnetism would not be developed until the work of James Clerk Maxwell emerged in the nineteenth century. However, an element of truth exists in Kepler's claim, as this light force is now known to be a contributory factor to the curved trail of dust that stretches out from a comet, always in the direction away from the sun. Maxwell (and, later, Einstein) deduced that light, although massless, has momentum just as a moving object or particle with mass does. When two moving objects collide they may rebound, each exerting a force on the other, thereby changing their direction of motion. The same principle can be applied when light is reflected from a surface, although the force exerted by the collision of each 'particle' of light (or photon) is almost immeasurably tiny. Nevertheless, in 1924 Friedrich Zander proposed harnessing this pushing as a means of propelling a craft through space just as a sailing ship is powered by the force of the wind. The 'solar sail' would receive the infinitesimal thrust provided by light from the sun which would, over time in the frictionless vacuum of space, accelerate it to high speeds.

But apart from interstellar travel, what are the consequences of light pressure for us on Earth? A short calculation reveals just how small the force from solar radiation that we are subjected to is: over one square metre of the earth's surface the light pressure is a mere 0.000 005 Newtons, 20 billion times smaller than the weight of the atmosphere on the same area. To measure the consequences of such miniscule light forces in the presence of such overwhelmingly large additional effects would be a challenging task even today, but the first direct measurement was made over a hundred years ago by Pyotr Lebedev, who was able to measure the force exerted by the reflection of light from a small mirror suspended by a thread in an evacuated glass jar. (Lebedev 1900). Even in the carefully controlled environment of Lebedev's experiment, and in the later experiments of Ernest Nichols and Gordon Hull (Nichols and Hull, 1901), heating of the surrounding gases causes a considerably greater effect than radiation pressure due to the light from the lamp; so what possible use could there be for such a force whose effects were almost unnoticeable? A practical application was only possible after the invention of an alternative source of light: the laser.

The nature of laser light is evident to anyone who has seen a laser light show in the night sky: it is extremely bright and highly directional - that is, it forms a narrow beam that spreads out only to a very small degree unlike, say, the light from a torch. These same features make it feasible to use

laser light as a means of exerting light pressure on matter on a more readily measurable scale. The first suggestion that this could be the case came from what might be considered an unusual source: the research laboratories of the Bell Telephone company in Holmdel, New Jersey. The Bell Labs, however, have been home to a remarkable array of scientists with interests stretching far beyond telecommunications, and as a result, the laboratory numbers amongst its alumni fifteen Nobel Laureates, with prizes awarded for discoveries in fields as diverse as radio astronomy and microelectronics.

The exploitation of light pressure was a long-standing ambition of Bell Labs physicist Arthur Ashkin. In the 1970s, Ashkin noted that when microscopic latex spheres were suspended in water, he could propel them along the path of a laser beam using the pushing force of radiation pressure so that they gathered at the wall of the container. By directing the laser beam vertically, the upwards thrust of the laser could be balanced by the downwards pull of gravity so that the spheres appeared to 'levitate' in space. While already an astonishing achievement, Ashkin wanted to go further and use only laser light and optical forces to 'trap' the spheres and smaller particles such as atoms. To a physicist, trapping a particle means fixing its location in space so that, should it move from its equilibrium position, it would experience a force that pulls it back again.
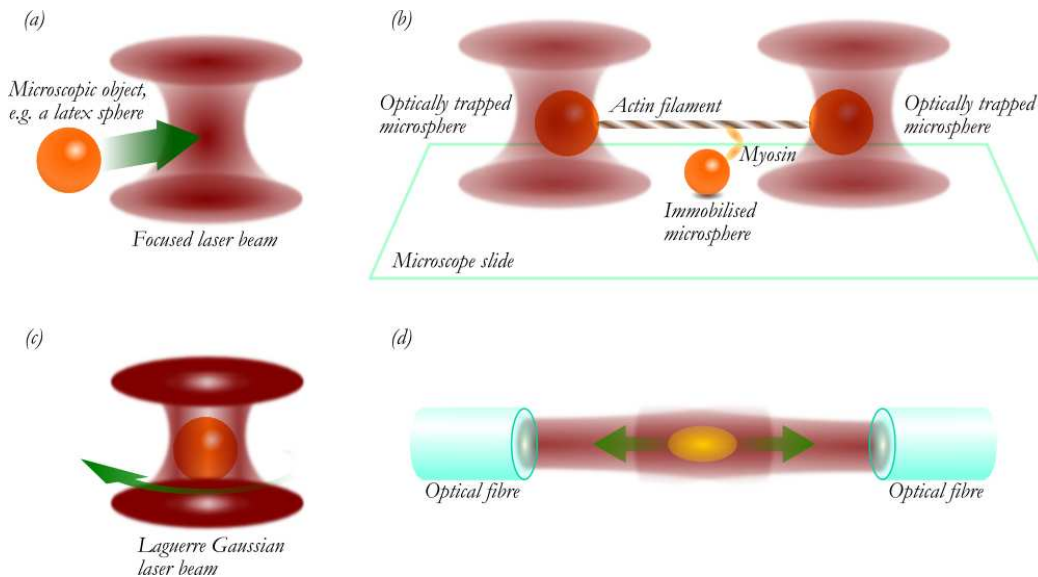

Figure 1: Optical trapping experiments. (a) A standard optical tweezers made by a single focused laser beam makes a 'trap' for microscopic particles which are attracted to the points of highest light intensity. (b) The dual tweezer experiment used to measure the mechanical properties of the myosin motor protein. (c) The 'optical spanner' uses a laser beam with special properties to rotate particles. (d) The 'optical stretcher' uses light emerging from a pair of optical fibres to deform an object, pulling opposite edges towards the fibres.

Ashkin's calculations revealed that such a pulling force could exist simultaneously with the pushing force of the laser beam. By imagining that the microscopic spheres behaved as tiny lenses, refracting the laser light and changing its direction, he realised that the light exerted a force not only along but also across the laser beam. Furthermore, the forces on opposite sides of the sphere were unbalanced, as a laser beam is brighter in the middle than at the edges. This gradient in intensity, he calculated, produced a force which always pulled the sphere to the middle of the beam where it was at its brightest. As a result, Ashkin could explain his earlier observations of particle propulsion and levitation as the intensity gradient force pulled the spheres across the beam to the most intense part, then pushed them along the beam path.

From there, Ashkin's master-stroke was to realise that he could make a similar intensity gradient force work in all three dimensions, and thereby trap a particle by laser light alone, if he focused the beam onto the spheres. Focusing the beam squeezes the optical power into a smaller area at

the focus before the beam diverges again. As a result, the peak intensity of the beam rises to a maximum at the focus before falling again. Since the microscopic spheres would seek out the point of highest intensity, Ashkin reasoned, they would make their way to the focus of the laser beam and remain there, provided that the pull of the intensity gradient force was sufficient to counter the push of the light pressure. This condition could be met by focusing the beam strongly with the high magnification lens that was already being used in the microscope in order to see the particles, as illustrated in part (a) of Figure 1. This new instrument for trapping microscopic matter using the forces of a single laser beam was demonstrated by Ashkin and his co-workers[1] at Bell Labs in 1986 (Ashkin 1986). Since the device could pick up and hold small particles with very fine control over their position using only laser light it soon became known as an *optical tweezers*.

Such a device might have been destined to become a laboratory curiosity that demonstrates some interesting but ultimately unimportant physics, if some practical use could not be found for it. Fortunately, the challenge was soon taken up by biologists who saw in optical tweezers a tool for holding and moving species such as cells and viruses that were of similar size to the latex spheres used by the Bell Labs team. Perhaps even more fortuitously, the force with which the particles were confined in the optical tweezers was also of a similar magnitude to those produced in important biological systems. Understanding the physics of optical forces, therefore, opened up the possibility of understanding more about the physical mechanisms behind the operation of a number of significant biological processes.

A particular triumph of optical tweezers has been in the study of biological systems that produce movement on the scale of single molecules. A mechanical motor such as the petrol engine in a car converts chemical energy into kinetic energy by burning fuel to drive a piston, the motion of which is ultimately transferred to the wheels. In muscles, movement is caused by the motion of the filaments of two different materials (actin and myosin) that slide past each other. The molecular 'motor' that produces this movement is the myosin molecule that uses a 'fuel' called Adenosine Triphosphate (ATP). The myosin molecule includes a structure that resembles a lever arm, one end of which attaches itself to the actin filament. Consuming the ATP fuel causes the lever arm to swing, pulling the actin filament past before releasing and swinging back ready to take hold and begin the cycle again. How far the lever arm swings and how hard it pulls can both be measured using optical tweezers.

The experiment uses two optical tweezers, each of which holds a microscopic latex sphere like those used in Ashkin's original experiments, illustrated in part (b) of Figure 1. Stretched taut between the spheres is an actin filament which, using the fine positional control possible with optical tweezers, is brought close to a third sphere that is covered with the molecular motor myosin and immobilised on a microscope slide. When the actin filament is within reach of the myosin, provided that enough ATP fuel is present, the myosin latches on and goes through its motor cycle, pulling the filament a short distance before letting go and starting the cycle again. The power stroke of the myosin is observed indirectly through the effect it has on the motion of the spheres at each end of the actin filament. When actin and myosin are not connected, the spheres are not static in the optical tweezers. As they are suspended in water they perform Brownian motion: random fluctuations in their position about an average or equilibrium position as a result of being bombarded from all directions by the water molecules. The size of these position fluctuations is small but measurable in the optical tweezers. When the myosin molecule catches on to the actin, the spheres no longer have the same freedom to move as they are connected - via actin, myosin and the third sphere - to the microscope slide, and a change in the size of the fluctuations is observed. When making the power stroke, the myosin motor pulls on the filament which in turn pulls on the sphere, trying to pull it away from its equilibrium position and out of the optical tweezers. By measuring how far the myosin pulls the sphere, both the length of the power stroke and the force applied can be measured. Pioneering experiments on

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[1] One of Ashkin's colleagues for these experiments was Steven Chu, who was awarded the Nobel Prize in 1997 for his work on optical trapping of atoms and is, at the time of writing, the US Energy Secretary.

this system were performed by scientists at Stanford University and King's College London (Finer 1994), who measured the size of the myosin molecule's 'step' to be 11 nm, and during the power stroke the molecule exerted an average force of 3-4 pN.[2] The researchers also varied the amount of ATP fuel available to the motor, and found that the variation only affected the speed of movement, and not the amount of force that the myosin could generate. It is important to know the mechanical properties of myosin, as recent work has shown that mutations of motor proteins, including others from the myosin family, can cause severe symptoms including deafness and cardiomyopathy. Further successful biophysical applications of optical tweezers have included the investigation of other families of motor proteins that perform different functions in the body, such as kinesin, and the flagellar or rotary motor that drives bacterial swimming motion.

The scope of optical tweezers for performing finely controlled manipulations of microscopic material can be widened by using laser beams with specially controlled properties. So-called '*Laguerre-Gaussian*' laser beams (named for the mathematical functions that describe the intensity in the beam) posses an unusual property in that the momentum of the light is not carried straight down the beam, but twists about the axis along a helical path. Consequently, such a laser beam has a point of zero intensity, a dark spot known as an optical vortex, at the centre. As a result of the spiralling momentum direction, such a beam can therefore not only exert a push or a pull on matter, but also cause a rotation. Indeed, when a Laguerre-Gaussian laser beam is used in optical tweezers, it can simultaneously trap and spin particles, as illustrated in part (c) of Figure 1, hence physicists have another item in their toolkit of optical manipulations, one that we could call an 'optical spanner'.

To date, most experiments that use light forces have been concerned with holding or moving rigid particles; however, a very recent innovation uses light forces to deform soft material. The 'optical stretcher', invented by Texas University physicists Josef Käs (now at the University of Leipzig) and Jochen Gück (now at Cambridge University), uses a pair of laser beam emerging from optical fibres to exert forces on microscopic material that act in opposite directions, thereby stretching it from each end, shown in part (d) of Figure 1. The principal targets of their investigations are cells whose resistance to stretching, or deformability, can change under certain circumstances. In particular, Gück's experiments are aimed at identifying cancerous cells that are stiffer, or less easily deformed, than healthy cells. By making an exact and quantitative measure of the deformability of individual cells as they pass through the laser beams, the intention is that the optical stretcher method will potentially eliminate any element of subjectivity in cancer cell detection. The device has very recently been shown to be capable of accurately quantifying the difference in deformability of oral cancer cells and cells from healthy patients, thereby demonstrating the potential of optical forces for mechanical testing of cells and broad screening of suspicious tumours (Remmerbach *et al.* 2009).

What does the future hold for optical trapping? A promising direction is the application of optical trapping methods in the emerging discipline of nanotechnology – the science of objects with dimensions between one millionth and one billionth of a metre (one micrometer to one nanometre). Nanometre scale particles, the most familiar of which are perhaps carbon nanotubes, show a variety of unusual properties that make them useful in the development of new technologies, and the sort of manipulations demonstrated by optical tweezers could potentially be useful in assembling nanoparticles to build them into larger structures in a controlled manner. Using simple optical tweezers to trap nanoparticles is, however, not a straightforward task as the effectiveness of the optical trap becomes limited by the fundamental physics of the trapping mechanism. While optical tweezers work very well for microscopic particles, the maximum trapping force decreases with the size of the particle. Indeed, for smaller particles the trapping force decreases with the third power of the size, that is, reducing the radius of a sphere by a factor of 10 would reduce the trapping force by a factor of 1000. Furthermore, nanometre scale particles suspended in liquid have significantly greater Brownian motion, so not only is the

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[2] 1 nm = 0.000 000 001 m, and 1 pN = 0.000 000 000 001 N.

optical trap much weaker, the nanoparticles are very likely to be pushed out of the trap by the motion of the water particles after only a short time (a few milliseconds).

Some varieties of nanoparticle, such as carbon nanotubes, have been used in optical tweezers as the length of the rod-shaped particle helps to make the trap stable (Maragò *et al.* 2008). Others, such as metallic nanorods, have unusual properties (e.g. a *plasmon resonance*) that can amplify the optical trapping force to add stability. An alternative approach is to use nanostructures to control the light field and hence the interaction of laser light with the target particles. This technique is presently under investigation in the UCL physics department where nanometre diameter optical fibres are being used for experiments aimed at trapping, sorting and delivering micro- and nanoparticles.[3]

In the four hundred years since Kepler's observations, the mechanical action of light on matter has been harnessed to become an indispensable tool for the control and probing of material on the microscopic scale. In addition to the experiments described here, light forces have found uses in a number of diverse fields including aerosol science, near-field optics, and microrheology. With new applications being discovered all the time, optical forces are sure to shed more light on the micro-world.

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[3] See the website www.ucl.ac.uk/~ucapphj