1 Introduction

The ability of light to exert forces has been known for quite some time. In fact, Johannes Kepler (1619) recognised that the tails of a comet – an example of which is shown in Fig. 1.1 – are due to the force exerted on the particles surrounding the comet's body by the Sun's rays. However, optical forces are extremely small; so small, in fact, that only in recent years, and only thanks to the advent of the laser, has it been possible to concentrate enough optical power into a small area to significantly affect the motion of microscopic particles, thereby leading to the invention of *optical tweezers*. Optical tweezers are generated by a tightly focused laser beam that can hold and manipulate a particle in the high-intensity region that is the focal spot. Optical tweezers and other optical manipulation techniques have heralded a revolution in the study of microscopic systems, spearheading new and more powerful techniques, e.g., to study biomolecules, to measure forces that act on a nanometre scale and to explore the limits of quantum mechanics. This book provides a comprehensive guide to the theory [Chapters 2–7], practice [Chapters 8–12] and applications [Chapters 13–25] of optical trapping and optical manipulation.

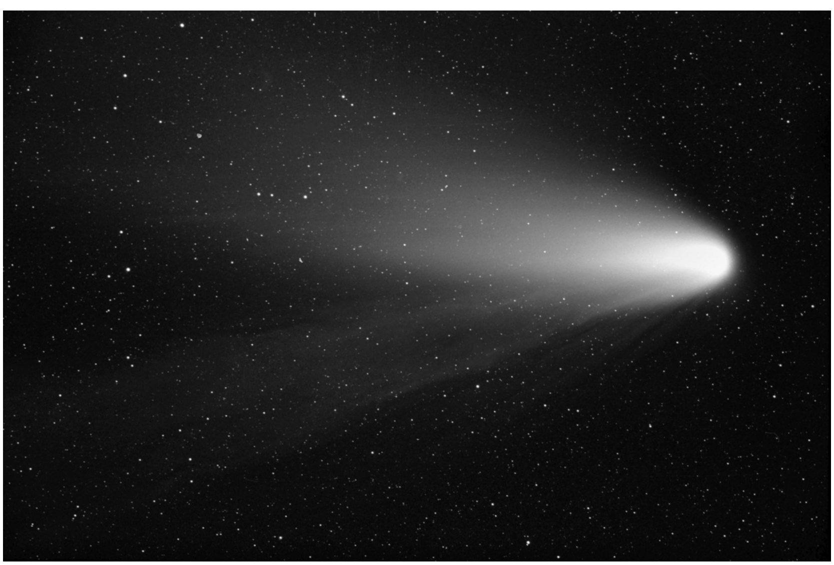

Figure 1.1 Optical forces in the sky. Besides the brightness of its coma, a comet is typically remembered by the length of its tails. Comet Hale–Bopp, which passed perihelion on 1 April 1997, lived up to expectations for it, boasting a blue ion tail (bottom) and a white dust tail (top) of exceptional extent, due respectively to the solar wind and to the Sun's light force. Credits: A. Dimai & D. Ghirardo, Col Druscie Observatory, Associazione Astronomica Cortina.

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1.1 A brief history of optical manipulation

Light's ability to exert forces has been recognised at least since 1619, when Kepler's *De Cometis* described the deflection of comet tails by the Sun's rays (Kepler, 1619). In the late nineteenth century, Maxwell's theory of electromagnetism predicted that the momentum flux of a light beam would be proportional to its intensity and could be transferred to illuminated objects, resulting in radiation pressure pushing objects along the beam's direction of propagation (Poynting, 1884). At the dawn of the twentieth century, several exciting early experiments were performed to detect these effects. Lebedev (1901) and Nichols and Hull (1901)[1] first succeeded in detecting radiation pressure on macroscopic objects and absorbing gases: when light from a lamp was focused onto a mirror attached to a torsion balance, the radiation pressure moved the balance from its equilibrium position. A few decades later, Beth (1936) reported the first experimental observation of the torque acting on a macroscopic object as a result of its interaction with light: he observed the deflection of a birefringent quartz wave plate suspended from a thin quartz fibre when circularly polarised light passed through it. These effects were so small, however, that they were not easily detected and any practical application seemed unfeasible. Quoting J. H. Poynting's presidential address to the British Physical Society in 1905:

> a very short experience in attempting to measure these forces is sufficient to make one realize their extreme minuteness – a minuteness which appears to put them beyond consideration in terrestrial affairs.[2]

This 'extreme minuteness' is the reason that optical trapping and manipulation did not exist before the invention of the laser in the 1960s (Townes, 1999).

In the early 1970s, Arthur Ashkin showed that laser-induced optical forces could be used to alter the motion of microscopic particles (Ashkin, 1970a) and neutral atoms (Ashkin, 1970b). In particular, Ashkin (1970a) showed that it was possible to use the radiation forces from a laser beam to significantly affect the dynamics of transparent micrometre-sized neutral particles, thereby identifying two basic light forces, a *scattering force* in the propagation direction of the incident beam and a *gradient force* along the intensity gradient perpendicular to the beam. He showed experimentally that using just these forces one could accelerate, decelerate and even stably trap small micrometre-sized neutral particles using focused laser beams.

[1] Nichols and Hull (1901) had found agreement with predictions from Maxwell's theory to within 1%. However, Bell and Green later reanalysed the data from these experiments and found several mathematical errors: Nichols and Hull had used an incorrect value for the mechanical equivalent of heat, taken some logarithms to base 10 instead of base e, and made several mistakes involving units and conversion factors. Once these mistakes were corrected, the results deviated from Maxwell's theory by 10%, which was still a success, but not nearly as good as the original 1% agreement. It is reasonable to believe that Nichols and Hull, finding such good agreement with Maxwell's theory, were happy to publish their results; if the mathematical errors had been in the opposite direction, they presumably would have checked their calculations more carefully. Worrall (1982) presents a fascinating history of this and other light pressure experiments. (Adapted from Jeng (2006).)

[2] Quoted by Ashkin (2000).

Ashkin started his analysis of optical forces by considering a beam of power P and angular frequency ω reflected by a plane mirror. It is well known from quantum mechanics that each photon of the beam carries a momentum, $p = \hbar\omega/c$, where $\hbar = h/(2\pi)$ is the reduced Planck constant, h is the Planck constant and c is the speed of light. In this case, there are $P/(\hbar\omega)$ photons per second striking the mirror, where $\hbar\omega$ is the energy carried by a single photon. If all of them are reflected straight back, the total change in light momentum per second, i.e., the force, is $2 \cdot (P/\hbar\omega) \cdot (\hbar\omega/c) = 2P/c$. By conservation of the total momentum of light and mirror, this implies that the mirror experiences an equal and opposite recoil force in the propagation direction of the light. This is the maximum force that one can extract form the light beam. Quoting Ashkin (2000):

> Suppose we have a laser and we focus our one watt to a small spot size of about a wavelength $\cong 1\,\mu\text{m}$, and let it hit a particle of diameter also of $1\,\mu\text{m}$. Treating the particle as a 100% reflecting mirror of density $\cong 1\,\text{gm/cm}^3$, we get an acceleration of the small particle $= A = F/m = 10^{-3}$ dynes/10^{-12} gm $= 10^9$ cm/sec^2. Thus, $A \cong 10^6$ g, where g $\cong 10^3$ cm/sec^2, the acceleration of gravity. This is quite large and should give readily observable effects, so I tried a simple experiment... It is surprising that this simple first experiment..., intended only to show forward motion due to laser radiation pressure, ended up demonstrating not only this force but the existence of the transverse force component, particle guiding, particle separation, and stable 3D particle trapping.[3]

Ashkin et al. (1986) reported the first observation of what is now commonly referred to as an *optical tweezers*: a tightly focused beam of light capable of holding microscopic particles in three dimensions. One of Ashkin's co-authors, Steven Chu, would go on to use optical tweezing in his work on cooling and trapping neutral atoms – research that earned Chu, together with Claude Cohen-Tannoudji and William Daniel Phillips, the 1997 Nobel Prize in Physics (Chu, 1998; Cohen-Tannoudji, 1998; Phillips, 1998).

Ghislain and Webb (1993) extended the capabilities of optical tweezers by devising a new kind of scanning probe microscopy that used an optically trapped microsphere as a probe. This technique, which was later called *photonic force microscopy*, provides one with the capability of measuring forces in the range from femtonewtons (10^{-15} N) to piconewtons (10^{-12} N), values well below those reachable with techniques based on microfabricated mechanical cantilevers, such as atomic force microscopy (Weisenhorn et al., 1989).

Since the early 1990s, optical trapping and optical manipulation have been applied to the biological sciences, starting by trapping an individual tobacco mosaic virus and an *Escherichia coli* bacterium (Ashkin et al., 1990). Block et al. (1990), Bustamante et al. (1994) and Finer et al. (1994) pioneered the use of optical force spectroscopy to characterise the mechanical properties of biomolecules and biological motors. These molecular motors are ubiquitous in biology, as they are responsible for locomotion, transport and mechanical action within the cell. Optical traps allowed these biophysicists to observe the forces and dynamics of nanoscale motors at the single-molecule level, leading to a greater

[3] In this quotation, we have kept the original cgs units used by Ashkin (2000). Except in direct quotations such as this, in this book we will consistently adopt SI units.

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understanding of the workings of these force-generating molecules (Bustamante et al., 2003; Neuman and Nagy, 2008). Since then, optical tweezers have also proven useful in many other areas of physics (Molloy and Padgett, 2002; Grier, 2003; Dholakia et al., 2008; Jonáš and Zemánek, 2008; Dholakia and Čižmár, 2011; Juan et al., 2011; Padgett and Bowman, 2011; Padgett and Di Leonardo, 2011), nanotechnology (Maragò et al., 2013), chemistry (Yi et al., 2006), soft matter (Löwen, 2001; Petrov, 2007) and biology (Müller et al., 2009; Capitanio and Pavone, 2013), as we will see in more detail in Chapters 13–25.

1.2 Crash course on optical tweezers

In the simplest configuration, depicted schematically in Fig. 1.2, an optical tweezers is generated by focusing a laser beam at a diffraction-limited spot using a high-numerical-aperture (NA) objective lens. This objective serves the dual purpose of focusing the trapping light and imaging the trapped object. Samples are often placed in a small (a few microlitres in volume) microfluidic chamber held on a microscope stage, which can be translated either by some manual actuators with sub-micrometric resolution or by piezo-driven actuators with nanometre position resolution. Generally, optical tweezers require little optical power, down to a few milliwatts, so that the risk of photodamage to, e.g., biological specimens is relatively small. The position of the optical trap can be controlled using, e.g., steerable mirrors. It is also possible to generate multiple optical traps by rapidly deflecting a single beam through several positions using, e.g., an acousto–optic deflector.

The focused laser beam acts as an attractive potential well for a particle whose refractive index is higher than that of its surrounding medium. The equilibrium position of the trapped particle lies near the focus.[4] When the object is displaced from this equilibrium position, it experiences an attractive force back towards it. This restoring force is, to a first approximation, proportional to the displacement. This means that along each direction, the optical forces associated with an optical tweezers can be described by Hooke's law, i.e.,

$$\begin{cases} F_x \approx -\kappa_x(x - x_{\rm eq}) \\ F_y \approx -\kappa_y(y - y_{\rm eq}) \\ F_z \approx -\kappa_z(z - z_{\rm eq}), \end{cases} \tag{1.1}$$

where $[x, y, z]$ is the particle's position, $[x_{\rm eq}, y_{\rm eq}, z_{\rm eq}]$ is the equilibrium position, and κ_x, κ_y and κ_z are the optical trap spring constants along the x-, y- and z-directions, usually referred to as *trap stiffnesses*. Therefore, an optical tweezers creates a three-dimensional potential well that can be approximated with three independent harmonic oscillators, one for each direction. If the optical system is well aligned, then for spherical microparticles, which are commonly used in optical tweezers, κ_x and κ_y are roughly equal, whereas κ_z is typically smaller by a factor between 2 and 10. In order to have an idea of the range of forces we are

[4] In fact, as we will see in Chapters 2–6, the equilibrium position is typically slightly displaced in the propagation direction of the optical beam because of the presence of scattering optical forces.

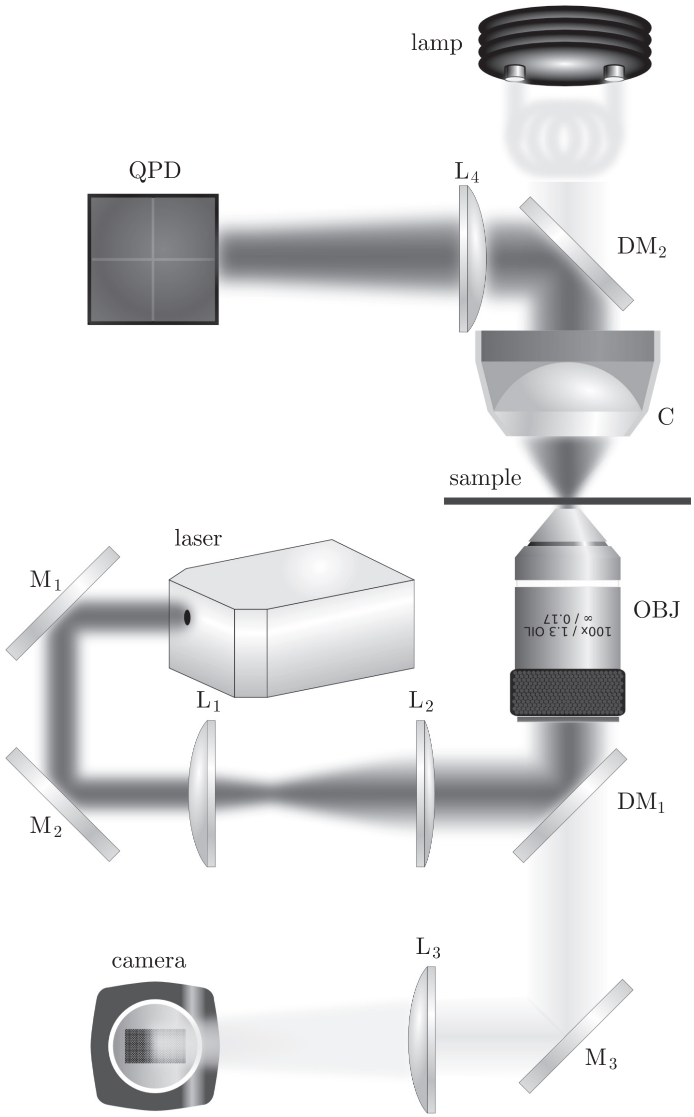

Figure 1.2 Basic experimental design. Optical tweezers are generated by focusing a laser beam on a diffraction-limited spot using a high-numerical-aperture objective lens (OBJ). Additional optics is needed to steer the optical tweezers position (beam-steering mirror M_2 and telescope formed by lenses L_1 and L_2), to image the sample (lamp, dichroic mirrors DM_1 and DM_2, camera lens L_3 and camera) and to track its position (condenser C, lens L_4 and quadrant photodiode QPD). The Brownian motion of the trapped particle can be tracked either by digital video microscopy or by interferometry and the measured particle trajectory can be used to calibrate the optical tweezers stiffness.

talking about, for a focused laser beam with power $P = 10\,\mathrm{mW}$, $\kappa_x \approx \kappa_y$ is on the order of $1\,\mathrm{pN}/\mu\mathrm{m} = 1\,\mathrm{fN/nm}$; however, this value can vary by as much as one order of magnitude depending on the experimental conditions, such as particle size and material, particle and medium refractive index, and lens numerical aperture. Finally, optical tweezers can generate

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not only forces, but also torques, e.g., by the transfer of the *spin angular momentum* associated with circularly polarised light, or of the *orbital angular momentum* associated with structured beams, or as a result of a particle's asymmetric shape (*windmill effect*).

Microscopic and nanoscopic particles undergo permanent *Brownian diffusion* because of collisions with the surrounding fluid molecules. Therefore, an optically trapped particle is, in fact, in a dynamic equilibrium between the thermal noise pushing it out of the trap and the optical forces driving it towards the equilibrium position. For the particle to remain within the optical trap, the optical potential well must be sufficiently deep. The depth of the optical potential is typically characterised in units of the thermal energy $k_B T$, where k_B is the Boltzmann constant and T is the absolute temperature, because this gives a characteristic energy scale for mesoscopic phenomena. The potential well of an optical tweezers should be at least a few $k_B T$ deep to be able to confine a particle. It is useful to keep in mind that at a typical and comfortable room temperature ($T = 300\,\mathrm{K}$) $k_B T = 4.14 \times 10^{-21}$ J.

The presence of Brownian noise does not exhaust the oddities of microscopic environments. In fact, when liquid environments are considered, inertial effects are absent at the microscopic scale because of the overwhelming role of viscosity; i.e., the particle lives at *low Reynolds numbers*. In order to get a feeling for this strange world, we will cite Purcell (1977):

> I want to take you into the world of very low Reynolds number – a world which is inhabited by the overwhelming majority of the organisms in this room. This world is quite different form the one that we have developed our intuitions in . . . It helps to imagine under what conditions a man would be swimming at, say, the same Reynolds number as his own sperm. Well you put him in a swimming pool that is full of molasses, and then you forbid him to move any part of his body faster than 1 cm/min. Now imagine yourself in that condition; you're under the swimming pool in molasses, and now you can only move like the hands of a clock. If under those ground rules you are able to move a few metres in a couple of weeks, you may qualify as a low Reynolds number swimmer.

The range of optical tweezer applications has been greatly expanded by the use of advanced beam-shaping techniques, where the structure of a light beam is altered by diffractive optical elements (DOEs) to produce multiple optical traps at definite positions and optical traps capable of imparting torques by the transfer of *orbital angular momentum*, e.g., Laguerre–Gaussian beams (Dholakia and Čižmár, 2011; Padgett and Bowman, 2011). Typically, a DOE is placed in a plane conjugate to the objective back aperture so that the complex field distribution in the trapping plane is the Fourier transform of that in the DOE plane. Often the DOE is a liquid-crystal spatial light modulator and is used to modulate just the phase of the incoming beam, as modulation of the amplitude of the beam would entail a loss of optical power. An optical tweezers incorporating such a device is often referred to as a *holographic optical tweezers* (HOT).

1.3 Optical trapping regimes

Optical trapping of particles is a consequence of the radiation force that stems from the conservation of (electromagnetic and mechanical) momentum. Historically, optical forces

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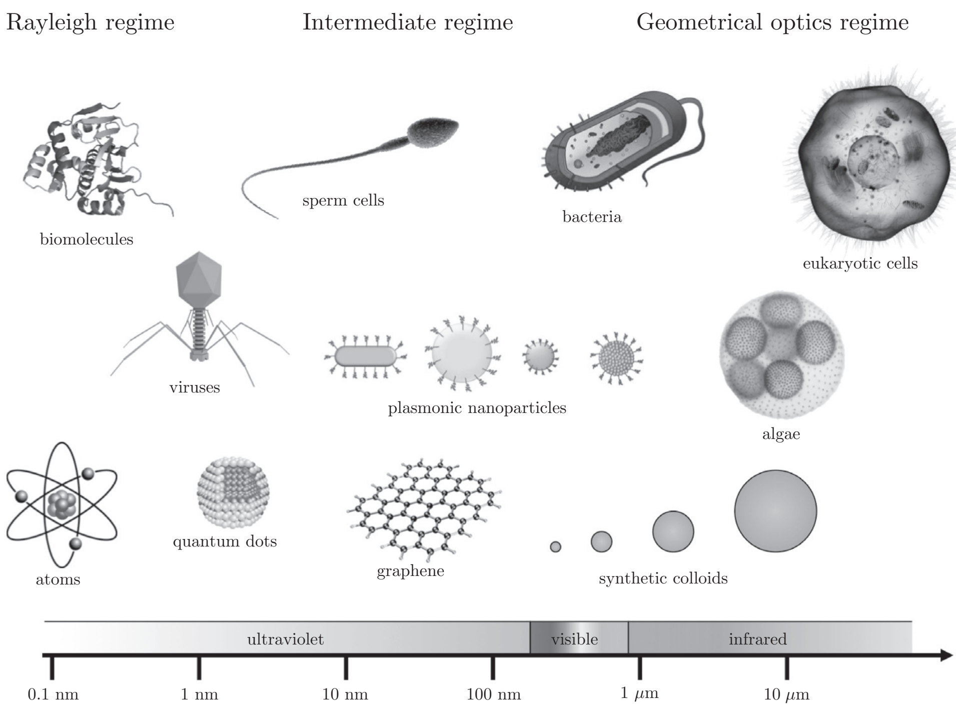

Figure 1.3 Optical trapping regimes. Trapping regimes and typical objects that are trapped in optical manipulation experiments. In defining the regimes of optical trapping, we have assumed trapping wavelengths that fall into in the visible or near-infrared spectral region.

have generally been understood through the use of approximations that depend on the size of the particle. Remarkable simplifications can be made in the calculation of the force exerted by optical tweezers when the particle size is much bigger – the *geometrical optics approximation* or *ray optics regime*, which is the subject of Chapter 2 – or much smaller – the *Rayleigh regime* or *dipole approximation*, which is the subject of Chapter 3 – than the trapping light wavelength. The importance of these approximate approaches is not only historical; they are often a valuable source of physical insight, as they are often amenable to analytical calculation and they can quickly give answers to complex problems. Nevertheless, when the particle's dimensions are comparable to the light wavelength, i.e., in the *intermediate regime*, a complete wave-optical modelling of the particle–light interaction is necessary for calculating the optical trapping forces, as we discuss in detail in Chapters 5 and 6. For homogeneous spherical particles, Mie theory can be used to generate accurate numerical results for essentially any size and refractive index; however, the situation becomes much more complex for non-spherical or non-homogenous particles. In fact, this is the case for most optical trapping experiments, where complex objects from tens of nanometres to tens of micrometres are manipulated, as shown in Fig. 1.3. Thus, in most cases, full electromagnetic calculations need to be used to have accurate predictions of the optical trapping behaviour.

The parameter most often used to determine the range of validity of these approaches is the *size parameter*,

$$k_{\mathrm{m}}a = \frac{2\pi n_{\mathrm{m}}}{\lambda_0}a, \tag{1.2}$$

where k_{m} is the light wavenumber in the medium surrounding the particle, a is the characteristic dimension of the particle, which in the case of a sphere corresponds to its radius, λ_0 is the trapping wavelength in vacuum, and n_{m} is the refractive index of the surrounding medium, which is typically water ($n_{\mathrm{m}} = 1.33$) or air ($n_{\mathrm{m}} = 1.00$). On one hand, ray optics is valid when $k_{\mathrm{m}}a \gg 1$ and its accuracy increases as the size parameter grows; because exact theories for nonspherical particles become impractical when $k_{\mathrm{m}}a$ exceeds a certain threshold due to the increase of their computational complexity, ray optics is in fact an extremely useful and effective approach for dealing with large particles. On the other hand, the Rayleigh approximation holds when a particle can be approximated as a dipole and the electromagnetic fields can be considered homogeneous inside the particle; this imposes two conditions on the size parameter,

$$\begin{cases} k_{\mathrm{m}}a \ll 1 \\ \left|\frac{n_{\mathrm{p}}}{n_{\mathrm{m}}}\right| k_{\mathrm{m}}a \ll 1, \end{cases} \tag{1.3}$$

where n_{p} is the refractive index of the particle.[5] The second condition in Eq. (1.3) needs to be considered with care, especially when dealing with nanostructures made of materials with high refractive index, e.g., silicon ($n_{\mathrm{p}} \approx 3.7$ at $\lambda_0 \approx 830\,\mathrm{nm}$), or when dealing with materials with a complex refractive index, e.g., plasmonic nanoparticles.

1.4 Other micromanipulation techniques

Apart from optical tweezers, several other micromanipulation techniques have been developed. In this section, we will briefly present *atomic force microscopy*, *magnetic tweezers*, *optoelectronic tweezers* and *acoustic tweezers*, focusing on their standing when compared to the optical tweezers technique. In fact, each of these techniques represents a fully fledged research field in its own right, and we will not make any attempt to discuss them in detail in this book.

Binnig et al. (1982) invented the *scanning tunnelling microscope*, which made it possible to resolve at the atomic level crystallographic structures (Binnig et al., 1983) and organic molecules (Smith et al., 1990). The *atomic force microscope* was invented a few years later by Binnig et al. (1986). These instruments have been successfully employed to study biological and nano-fabricated structures, overcoming the traditional diffraction limit of

[5] In fact, the dipole approximation can be derived from Mie theory by expanding the Bessel functions in the solutions under the assumption that Eq. (1.3) holds true (Mishchenko et al., 2002).

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optical microscopes. Furthermore, they have developed from pure imaging instruments into more general manipulation and measuring tools capable of operating at the level of single atoms or molecules. However, all these techniques require a macroscopic mechanical device to guide their cantilevers, so the force range they can probe is substantially higher (nanonewtons) than that which is accessible with optical tweezers (from piconewtons down to femtonewtons).

A *magnetic tweezers* uses a set of magnets to produce a strong magnetic field gradient that is used to exert a force on a microscopic superparamagnetic particle (Smith et al., 1992; Neuman and Nagy, 2008). The force is varied by modulating the position of the magnets relative to the bead and, because usually the magnets are millimetres in size whereas the bead is only allowed to move by a few micrometres, the applied magnetic force can be regarded as constant for a given position of the magnets. A very interesting feature of the magnetic tweezers technique is its ability to rotate the magnetic bead, e.g., allowing one to easily twist a molecule tethering the bead to the sample. Although the laser beam of an optical tweezers may also interact with other particles of the sample because of contrasts in the refractive index, the magnetic interaction is highly specific to the superparamagnetic microparticles used and therefore practically does not affect the sample. Also, as a consequence of the low trap stiffness associated with magnetic forces, the range of forces accessible with magnetic tweezers is lower than with optical tweezers.

Optoelectronic tweezers use projected images to trap and manipulate large ensembles of particles (Chiou et al., 2005). They are intrinsically two-dimensional and work by pushing the particles against a planar surface: an electric potential difference is applied between the two walls of a sample cell and then light is used to create some reconfigurable electrodes on one of the surfaces. In this way, a non-uniform electromagnetic field is obtained and particles are moved accordingly because of dielectrophoresis. Optoelectronic tweezers have an advantage over conventional optical tweezers in that they can use non-coherent light sources and require several orders of magnitude less power so that several thousands of particles can be manipulated in parallel. They cannot, however, be used to manipulate particles in three dimensions or to measure forces acting on nanoscopic length scales.

Not only electromagnetic waves, but also acoustic waves can generate a radiation force. In fact, the field of a standing wave produced by two collimated ultrasound transducers can trap polymer spheres, biological cells, grass seeds and microbubbles at either nodes or antinodes along the beam axis. This trapping technique is referred to as *acoustic tweezers* (Wu, 1991) and has versatile applications in the separation, concentration and localisation of particles. Based on the concept of optical tweezers, Lee et al. (2005) suggested theoretically that a trapping effect can be produced by a single focused acoustic beam using a highly focusing ultrasonic transducer with a ratio of focal length to transducer diameter near 1, i.e., the acoustic equivalent of a high-NA objective, driven at high frequency (≈ 100 MHz) and high pressure (≈ 1.5 MPa). A single-beam acoustic device, with its relatively simple scheme and low intensity, can trap a single lipid droplet in a manner similar to optical tweezers. Forces on the order of hundreds of nanonewtons direct the droplet towards the beam focus, within a range of hundreds of micrometres. This trapping method, therefore,

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can be a useful tool for particle manipulation in areas where larger particles or forces are involved and for manipulations over longer distances, as Lee et al. (2009) demonstrated experimentally. The main advantage of acoustic tweezers over optical tweezers lies in their being able to exert much larger forces, i.e., nanonewtons, and in acoustic waves having a much greater penetration depth in fluids and biological materials.

1.5 Scope of this book

This book provides a comprehensive guide to the theory, practice and applications of optical trapping and optical manipulation. The material expounded in this book, together with the material provided on the book website (www.opticaltweezers.org), will provide a working knowledge of optical trapping and manipulation sufficient to build an optical tweezers apparatus and operate it to perform an experiment and to calculate optical forces.

Part I [Chapters 2–7] presents the theoretical foundations needed to understand the physics behind optical trapping, including both the theory of optical forces and the theory of Brownian motion. Chapter 2 is dedicated to the geometrical optics approximation and also provides an intuitive overview of many concepts that give insight into the mechanism by which microscopic particles can be optically trapped. Chapter 3 deals with optical forces in the dipole approximation and introduces the concept of optical binding. Chapter 4 provides a detailed introduction to optical beams, their properties and their focusing. Chapters 5 and 6 are dedicated to the exact treatment of optical forces based on electromagnetic light scattering, focusing on the Mie scattering theory and the transition matrix (T-matrix) approach; the discrete dipole approximation (DDA) and finite-difference time domain (FDTD) methods are also briefly introduced. Together, these two chapters cover the core material needed for any accurate electromagnetic study of optical forces. Finally, Chapter 7 reviews the main properties of the Brownian motion that come into play when dealing with optical trapping and manipulation and that are necessary to understand the dynamics of optically trapped particles.

Part II [Chapters 8–12] deals with the experimental practice of optical trapping and manipulation. Chapter 8 presents a step-by-step guide to the realisation of a simple optical tweezers set-up starting from scratch, assuming only a minimum level of experimental knowledge on the part of the reader. Chapter 9 gives a detailed account of how to acquire and analyse data from optical tweezers. Chapter 10 expounds upon how to employ optical tweezers to measure nanoscopic forces and torques, i.e., the use of an optical tweezers as a photonic force microscope. Chapter 11 explains how to work with holographic optical tweezers, including, in particular, the calculation of diffraction patterns that produce a given intensity distribution in the trapping plane. Finally, Chapter 12 reviews a series of alternative and advanced optical manipulation techniques, including spectroscopic tweezers, fibre optical tweezers, evanescent optical traps, feedback optical tweezers and haptic optical tweezers.

Part III [Chapters 13–25] gives detailed reviews of various fields of application for optical trapping and manipulation. First, Chapters 13 and 14 give an overview of how optical tweezers have found application in molecular biology and cell biology, respectively. Then, Chapters 15 and 16 explore how optical tweezers have been successfully combined with spectroscopic and optofluidic techniques. Afterwards, a series of chapters are dedicated to how optical tweezers have been used to study phenomena in soft matter and colloid science [Chapter 17], microchemistry [Chapter 18], aerosol science [Chapter 19], statistical physics [Chapter 20] and nanoscopic thermodynamics [Chapter 21]. Finally, we consider the development of optical tweezers towards the nanoscopic world and, in particular, plasmonic optical tweezers [Chapter 22], nanotweezers [Chapter 23], atom trapping [Chapter 24] and optical trapping of mesoscopic objects towards the quantum regime [Chapter 25].

1.6 How to read this book

While we have striven to keep the treatment of the material at a level accessible to advanced undergraduate or beginning graduate students, we hope that the depth and breath of the topics covered in this book will provide a useful resource even for experienced practitioners. In fact, this book can be read at different levels, from the interested layman level to the specialist level. In order to afford such flexibility without overloading the main text of the book, we have embedded in the body of the chapters of Parts I and II a series of exercises, whose results are often explicitly stated in the exercises themselves, and are in fact part of the content of this book. We are sure every reader will easily find his or her most convenient way through this book; nevertheless, here we give some suggestions on how to read this book depending on the reader profile:

- **Interested scientists**: We suggest starting from the applications explained in Part III and then moving on to Parts I and II, skipping all exercises and Chapters 5 and 6, as, even with this omission, one can get a very good feeling for what optical tweezers are, how they work and in which fields they are employed.
- **Practitioners**: We suggest starting from any of the chapters in Parts I and II they find most useful and perusing (at least) the exercises in the text of the chapters they are planning to use in their research.
- **Theoreticians**: We suggest studying Part I in depth with all exercises and quickly reading Part II (without exercises). In particular, we highlight that the theoretical treatment is accompanied by a software package for the treatment of optical forces and Brownian motion.
- **Experimentalists**: We suggest quickly reading Part I (without exercises and skipping Chapters 5 and 6 at a first reading) and studying Part II in depth. In particular, we highlight that Chapter 8 provides a step-by-step guide to the construction of an optical tweezers from scratch and without assuming any previous knowledge of the field, that Chapter 9 provides a detailed explanation of the technique for acquiring and analysing

optical tweezers data, and that Chapter 11 provides an in-depth explanation of how to operate holographic optical tweezers.

1.7 OTS - the Optical Tweezers Software

Together with this book, we have developed a comprehensive MatLab software toolbox to work with optical tweezers – `OTS - the Optical Tweezers Software`. `OTS` is freely available for download from www.opticaltweezers.org. Like this book, `OTS` covers both the theory and the practice of optical trapping and manipulation. For the theoretical part, we have developed packages to calculate optical forces within the geometrical optics approximation (`go`), the dipole approximation (`da`) and the full electromagnetic theory (`mie` and `emt`); furthermore, we provide some code to perform Brownian dynamics simulations of optically trapped particles (`bm`). For the practical part, we provide codes to perform digital video microscopy (`dvm`), optical tweezers calibration and force measurement (`pfm`), and holographic optical tweezers (`hot`). All these codes are based on our research experience and are developed to the point where they can be readily used in research.

`OTS` is fully documented, accompanied by code examples and ready to be employed to explore more complex situations in learning, teaching and research. In fact, we have implemented `OTS` using an object-oriented approach so that it can easily be extended and adapted to the specific needs of users; for example, it is possible to create more complex optically trappable particles in the geometrical optics approximation by extending the objects provided for spherical, cylindrical and ellipsoidal particles. In particular, we have used `OTS` to prepare most of the original figures in this book.

The `OTS` package contains the following subpackages:

- `OTS.m` - (file) : Load the software packages
- `utility` - (directory) : General utility functions
- `tools` - (directory) : Common tools
- `shapes` - (directory) : 3D geometrical shapes
- `beams` - (directory) : Optical beams
- `go` - (directory) : Geometrical optics
- `da` - (directory) : Dipole approximation
- `mie` - (directory) : Mie particles
- `emt` - (directory) : Electromagnetic theory
- `bm` - (directory) : Brownian motion
- `dvm` - (directory) : Digital video microscopy
- `pfm` - (directory) : Photonic force microscopy
- `hot` - (directory) : Holographic optical tweezers

All the documentation for the installation and use of the `OTS` package is available from the book website (www.opticaltweezers.org).

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