The zoo of nonconservative optical forces

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Abstract. Optical forces are usually described as conservative ones originating from intensity gradients in optical tweezers. However, the fundamental optical action on matter is nonconservative. In contrast to gradient forces, the spectrum of action of nonconservative forces is much wider: they can propel, pull, rotate objects or move objects along complicated trajectories. Different manifestations of nonconservative optical forces will be reviewed and their dependence on the specific spatial properties of optical fields will be discussed. New developments relevant to the nonconservative optical forces such as negative forces (tractor beams) and transversal forces will also be discussed.

1. Introduction
The first indication that light can exert a force came from comet tails, observed to point away from the Sun. Back in the 17-th century, Kepler predicted that those tails were driven by the pressure of sunlight, and this conjecture still holds true for the many comet tails which consist of dust. Since then, sustained experimental attempts tried to test the concept of light pressure, the simplest manifestation of nonconservative optical force (NCF). The invention of lasers with their high intensity and directional beams produced new interest in optical forces. However, the main attention shifted to trapping particles at lasers’ focal spot, the mechanism that relies on conservative gradient forces.

In contrast to gradient forces, the spectrum of action of nonconservative forces is much wider: they can propel, pull, rotate objects or move objects along complicated trajectories \cite{1}. In contrast to conservative traps, nonconservative forces can produce mass manipulation of particles \cite{2} or exert forces on macroscopically large objects (such as solar sails). However, the full range of applications of nonconservative forces still needed to be discovered.

2. Manifestations of nonconservative optical forces
Although different theoretical models have been employed to describe the optical forces acting on matter, they all can be traced to a common source: the exchange of momentum between radiation and matter: photons carry momentum and momentum conservation laws apply whenever a beam of light changes its direction due to refraction, reflection or scattering. But even with this simple interpretation and with a plane wave serving as an illumination source, NCFs can have very unexpected manifestations. For example, when particles are located at the interface of two media with different dielectric properties, the mechanical action of illumination may acquire additional features due to the transformation of linear momentum at the interface. In particular, the momentum of electromagnetic
wave increases when light propagates into more optically dense medium. One interesting consequence is the appearance of attractive optical forces for surface-bound particles that were observed experimentally for droplets of oil on water surface [3]. The presence of plasmonic interfaces can generate other interesting effects. For instance, if a small particle is located near an interface and it is illuminated by a linearly polarized field, it can manifest a rotating dipole which appears because of the interference between the incident and the reflected waves. This rotating dipole excites asymmetrically propagating surface plasmon-polariton waves as shown in Figure 1. As the wavenumber of surface plasmons is larger than the one in free-space, the momentum of scattered wave effectively increases because of the surface plasmon wave propagating in the forward direction. This excess of linear momentum leads to the appearance of a negative force acting on the object (“plasmonic tractor beam”) [4]. Besides negative, the lateral force can also exist in the case of circularly polarized plane wave excitation of particles next to the dielectric or plasmonic interfaces [5].

![Figure 1. The schematics of negative force F appearance for a particle located next to the plasmonic interface. The interference of incident and reflected waves creates rotating dipole moment, which excites asymmetric surface plasmon-polariton (SPP) wave resulting in a recoil force acting on the particle.](image1)

The simplest extension of the case of a single plane wave, two-wave interference, brings a whole new range of optomechanical phenomena. Notably, in this case, the Poynting momentum density may not coincide with the canonical momentum. This can lead to transversal optical forces which point perpendicular to the direction of propagation of both waves, an effect that was detected experimentally [6] (Figure 2).

![Figure 2. Scattering of two orthogonal waves (linearly l and circularly c polarized for this particular example) results in a nonconservative force F_AB acting on a scattering particle in a direction perpendicular to both wavevectors k_l and k_c. The entire geometry resembles the setting of the Aharonov-Bohm (AB) experiment [6].](image2)

In the case of two or more overlapping waves (structured field), the interference between different multipoles can increase forward scattering and induce NCF acting in a direction opposite to the overall
energy flow creating, so called, tractor beam [7]. Another example of structured field are Airy and other curved beams, which allow transport of particles along curved trajectories [8].

3. Conclusion
Nonconservative optical forces manifest themselves at all possible scales starting from atomic and up to cosmic dimensions. Even in the context of man-made devices, the nonconservative optical forces play a significant role from large-scale machines such as the LIGO interferometer down to the scales of micro-particles. There is a variety of effects ranging from the simple radiative pressure in a plane wave to the unexpected existence of negative and transversal forces acting on complex particles placed in structured fields. Nonconservative optical forces accompany a number of intriguing phenomena such as light momentum transformation in dielectric media, weak values of momentum near vortices and in evanescent fields or the elusive Belinfante momentum in structured fields. Understanding the intricacies of these nonconservative forces still raises fundamental questions and may open new possibilities for mechanical manipulation that go beyond the direct transfer of linear momentum from the electromagnetic field to a material body.

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