Non-conservative Optical Forces on Nanoparticles

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We will address some basic questions related to the light forces on small (Rayleigh) particles, which are usually described as the sum of two terms: the dipolar or gradient force and the scattering or radiation pressure force. The scattering force is traditionally considered proportional to the Poynting vector, which gives the direction and magnitude of the momentum flow. However, as we will show, when the light field has a non-uniform spatial distribution of spin angular momentum, an additional scattering force arises as a reaction of the particle against the rotation of the spin. This non-conservative force term is proportional to the curl of the spin angular momentum of the light field [1].

We analyze the forces on a small dipolar particle and the electromagnetic momentum density in a configuration consisting in two perpendicular linear [1,2] and circularly [3] polarized stationary waves. The field distribution shows regions in which the electric and magnetic fields are parallel corresponding to a null Poynting vector. Although the average value of the momentum density, proportional to the Poynting vector, is zero in these regions, there are scattering forces acting on small particles due to light's spin force. The total scattering force suggests a new definition of the average value of the momentum density for free propagating electromagnetic fields [3].

The unusual properties of the optical forces acting on nanoparticle chains [4] as well as on particles with both electric and magnetic response [5] will also be analyzed. We will see that a chain made of metallic nanoparticles can be used as a resonant light sail, attached by one end point to a transparent object and propelling it by the use of electromagnetic radiation. Interestingly, there is a window in the frequency spectrum in which null torque equilibrium configuration, with minimum geometric cross section, corresponds to a maximum in the driving force. We finally focus on nanometer-sized spheres of conventional semiconductor materials, like Silicon (Si) or Germanium (Ge), which have extraordinary electric and magnetic optical properties in the infrared-telecom range of the electromagnetic spectrum [6-8]. These particles play a key role as pulling probes in the recent proposal of Laser Tractor Beams [9,10].

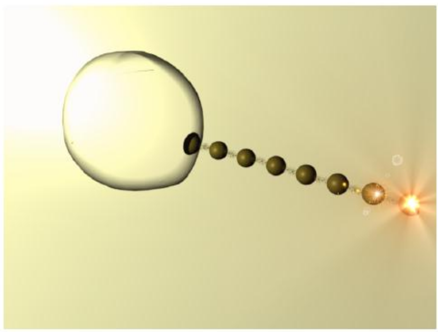

Figure 1: Sketch representing a light sail composed of a gold nanoparticle chain. (After Ref.[4]).

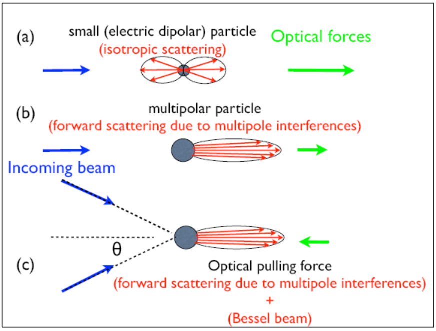

Figure 2: (a) For small dipolar particles scattering is isotropic. There is a net force on the particle along the forward direction (the same direction of the incoming beam) due to the conservation of the total momentum. (b) Due to the interference between multipolar fields, the scattering can be strongly focused in the forward direction. The total force forward is reduced. (c) As the angle between the beams increases, the traditional radiation force goes to zero as the cosine of the angle, whilst the contribution to the force coming from the strongly focused forward scattering remains finite. Above a given angle, there is an optical pulling force against the photon stream. (After Ref.[10]).

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