Optical forces: some fundamentals and some surprises

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Abstract – **We address the general problem of evaluating optical forces on general dielectric and magneto-dielectric materials. Our starting point is the familiar Lorentz force law and we exploit symmetries and physical reasoning to build up a complete theory. At the quantum level, this allows us to identify the mechanical properties of photons propagating through such media.**

That light has mechanical properties has been known for centuries, at least since the speculations of Kepler and Newton. Maxwell, in his treatise on electricity and magnetism, carried out an accurate calculation of the radiation pressure of sunlight on the surface of the earth [1]. Today, such optical forces are exploited with exquisite control in optical micromanipulation and in the laser cooling of individual atoms.

There remain surprises in the interaction of light with matter and, in particular, the mechanical effects of light on matter. This talk will present some of these, starting with a paradox which points to the existence of a fiction force acting on a radiating atom in an otherwise empty region of space [2].

We shall build from first principles by examining in some detail the optical force on a dipole atom and reveal some of the subtleties necessary for an accurate evaluation of the forces, including the Röntgen interaction term $(\mathbf{d}\times\mathbf{B}).\mathbf{p}$. From this we can construct an expression for the force-density on a dielectric medium and use this to evaluate the radiation forces acting on such a medium [3,4].

The transition to materials with important magnetic responses is handled most elegantly by exploiting a symmetry, due to Heaviside and Larmor [5,6], between the electric and magnetic fields for Maxwell's equations in the absence of free charges and currents. Pleasingly, this approach leads to a force density [7] that agrees with that proposed by Einstein and Laub [8].

The forces on magnetic media naturally contain contributions related to the so-called hidden momentum; indeed these play a role for magnetic media that is closely related to that of the Röntgen interaction for electric dipoles. Both play an important role in the long-standing Abraham-Minkowski [9,10] dilemma concerning the correct form of the momentum of light in a medium and in its resolution [11,12].

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