Blackbody Radiation Forces

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Abstract The van der Waals (vdW) force describes the interaction between atoms at submicron separations while the Casimir-Polder (CP) force is applicable an atom separated from a surface by a few microns. The CP force assumes the surface is at zero temperature and is derived based on zero point fluctuations (ZPF) of the electromagnetic (EM) field. Lifshitz extended the CP force to allow finite temperatures for the surface by specifying temperature dependent dielectric properties. But the temperature of the surface cannot be known without prior heat transfer analysis, and therefore a new approach to the force on an atom is proposed. Instead of the ZPF, the derivation is based on EM blackbody (BB) radiation emitted from the surface, thereby allowing the force on the atom to be determined along with the surface temperature in a heat transfer analysis. The BB force is shown to decay by $1/z^5$ and only depend on the polarizability of the atom. The BB force supersedes the CP force at separations of a few microns, but not the vdW force at submicron separations without further study.

Keywords: van der Waals, Casimir, Polder, Lifshitz

I. Introduction

In 1948, Casimir [1] derived the attractive force between a pair of electrically neutral metal plates in a vacuum based on the ZPF of quantum mechanics. Similarly, the ZPF forms the basis for the vdW forces between atoms and the CP forces [2] between atoms and surfaces.

But ZPF may have unnecessarily misled research on atom forces. Other forms of EM radiation may also produce forces on the atom, but have been neglected to date. For example, the force from BB radiation is not included in vdW and CP forces. This is unfortunate because unlike the ZPF which is speculative, BB radiation is undeniable.

BB forces aside, Lifshitz [3] extended the ZPF to allow finite temperatures to be included in the CP force by specifying temperature dependent dielectric properties for the surface. For separations larger than the thermal photon wavelength hc/kT, the Lifshitz (L) force decays by $1/z^4$. Here, h is Planck's constant, c is the speed of light, k is Boltzmann's constant, and T is absolute temperature.

In contrast to the thermal equilibrium assumed by Lifshitz, Henkel et al. [4] proposed the notion of non-equilibrium (NEQ). NEQ means the dielectric surface was assumed to be at a finite temperature with the surroundings at zero temperature, i.e., all interacting surfaces were not at the same temperature. Only the force at submicron separation was studied.

Recently, Antezza et al. [5] extended the NEQ interaction of atoms with a surface. Depending on whether the temperature of the surface is different than that of the surroundings, the attractive force at thermal photon wavelength separations decayed by $1/z^3$ and could even be repulsive. Measurements [6] of rubidium atoms interacting with quartz surfaces using the Bose-Einstein Condensate (BEC) method by Obrecht et al. [6] was found in agreement with the NEQ theory [5].

In this paper, the effects of temperature on the atom forces are not simulated by temperature dependent dielectric properties. Instead, the BB force is determined from the interaction of the atom with the thermal BB radiation emitted along with the surface temperature in a heat transfer analysis. Although a heat transfer analysis for a specific thermal loading is not conducted, the approach that one would take to determine the BB force along with the surface temperature is otherwise obvious. Only the surface temperature and polarizability of the atom is necessary to determine the BB force.

II. Analysis and Results

The force induced [5] on an atom depends on the gradient of the EM field. For the surface in the x-y plane, the BB radiation emitted in direction z induces force F_{BB},

$$F_{BB} = 4\pi\alpha_o \frac{\partial U}{\partial z} \tag{1}$$

where, α_o is the polarizability of the atom and U is the electric energy density of the surroundings,

$$U = \frac{\langle E^2 \rangle}{8\pi} \tag{2}$$

and E is the electric field of the BB radiation. From the BB radiation equations, the energy density U is,

$$U = 8\pi hc \int \frac{1}{\lambda^5}(\exp(\frac{hc}{2zkT}) - 1)^{-1} d\lambda \tag{3}$$

where, λ is the wavelength. The atom interacts with the surface through a standing wave. For the atom located a distance z from the surface, the standing wavelength $\lambda = 2z$ gives the energy density U,

$$U = \frac{\pi}{2} hc \int \frac{1}{z^5}(\exp(\frac{hc}{2zkT}) - 1)^{-1} dz \tag{4}$$

Since $\frac{\partial}{\partial z}\int f(z)dz = f(z)$, then

$$\frac{\partial U}{\partial z} = \frac{\pi}{2z^5} hc(\exp(\frac{hc}{2zkT}) - 1)^{-1} \tag{5}$$

Combining, the BB force,

$$F_{BB} = 2\pi^2 \alpha_o hc \frac{1}{z^5}(\exp(\frac{hc}{2xkT} - 1)^{-1} \tag{6}$$

The BB force is observed to decay by $1/z^5$. The CP force F_{CP} [5] also decays by $1/z^5$,

$$F_{CP} = \frac{3}{2\pi}\hbar c \alpha_o \frac{1}{z^5}\frac{(\varepsilon_o - 1)}{(\varepsilon_o + 1)}\phi(\varepsilon_o) \tag{7}$$

The Lifshitz force F_L decays by $1/z^4$,

$$F_L = \frac{3}{4} kT\alpha_o \frac{1}{z^4}\frac{(\varepsilon_o - 1)}{(\varepsilon_o + 1)} \tag{8}$$

For rubidium, α_o = 47.3x10^{-30}m^3. The BB force at 310, 479, and 610 K, and CP, L, and NEQ forces for quartz surface having ε_o = 3.8 are shown in Fig. 1

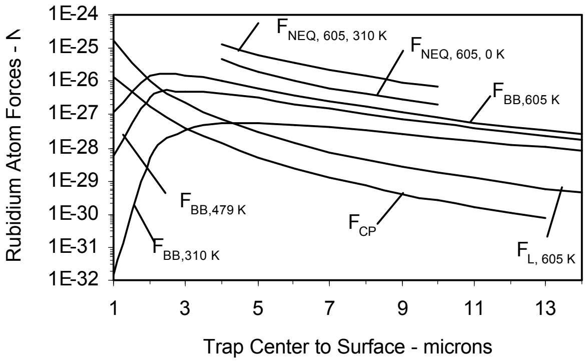

Figure 1. BB, CP, and L Forces
Rubidium Atom adjacent Quartz Surface

Over the z = 6 to 14 micron range, the BB forces at 310, 479, and 605 K are observed to be about 2 orders of magnitude greater than the CP and L forces. Extrapolation of asymptotic CP and L forces below 6 microns is not valid. In contrast, the BB forces are valid over the full range tend to vanish as the z distance approaches zero. However, the vdW force exceeds the BB force below about 1 micron.

The out of thermal equilibrium force F_{NEQ} (Fig. 2 of [5]) for the surface at 605 K and surroundings at 310 K are shown to be higher than all others. For the surface at 605 K and surroundings at 0 K, the NEQ forces tend to approach the BB force at 605 K.

Similar to [6] the BB forces and the ratio of the force at 605 K to that at 479 and 310 K over the range of z from 6 to 14 microns is shown in Figs. 2 and 3, respectively. At 605 K, Fig. 2 shows the BB force at z = 7 microns is about $2.5x10^{-27}$ N. In the BEC experiments, the ratio of the CP force at 605 K to that at 310 K was found [6] to be about 3. For BB forces, Fig. 3 shows ratios as high as 6 at z = 7 microns. However, the ratio of the BB force at 479 K to that at 310 K is about 3.

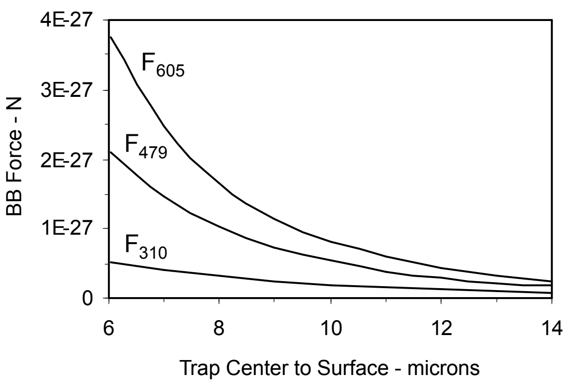

Figure 2. BB Forces for Rubidium Atom
Range z = 6 to 14 microns

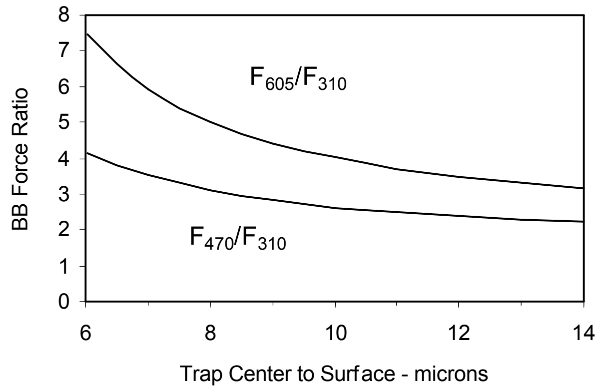

Figure 3. BB Force Ratios for Rubidium Atom
Range z = 6 to 14 microns

III. Summary and Conclusions

The vdW and CP force for the interaction of atoms with surfaces need not be based on the speculative ZPF. BB radiations at temperature are real and above question. The BB forces between an atom and surface therefore provide a physical alternative to the unphysical ZPF embodied in vdW and CP forces.

The BB forces only depend on the polarizability of the rubidium atom and the BB radiation at the temperature of the surface, the latter defined by a heat transfer analysis of the specific thermal loading conditions. Unlike the CP force, the BB force does not depend on dielectric properties, but rather on thermal conductivity, specific heat, and density.

BB radiation allows an understanding of NEQ between the temperature of the surface and the surroundings. For an atom near a hot surface, the BB radiation from relatively cold surroundings should not affect the atom force. Indeed, as the distance z increases, the BB force decreases making the effect of the surroundings insignificant. However, hot surroundings are likely to raise the temperature of the surface adjacent the atom and in that way affect the BB force.

Moreover, the BB force is always attractive and cannot be made repulsive by making the surface colder than the surroundings. The notion the CP force can be separated into internal fluctuations and those that undergo external reflection at the surface having opposite sign leading to a cancellation at thermal equilibrium is only true if the atom is halfway between identical surfaces. Usually the atom is near one surface, and therefore the BB force is controlled by the temperature of the adjacent surface alone.

The BB radiation force depends only on the instantaneous temperature of the surface and is independent of ZPF. Since the BB radiation is real while the ZPF remains speculative, and since the CP forces are reasonably upper bound by the BB force, the BB force at separations beyond a few microns is proposed to supersede CP forces.

However, the BB force does not upper bound the vdW force between atoms at submicron separations. But QED induced EM radiation increases the frequency of FIR emission from an atom in close proximity to another to high levels, thereby may produce a BB force comparable to the vdW force, but requires further study.

IV. Extensions

Currently, Newtonian gravity at length scales of 10 microns is an active area of research. One method [7] developed at Stanford employs a 2 inch diameter hemispherical helium gas bearing operating at cryogenic temperatures. Viewed from above, the flat bearing surface is configured into 100 short segments of lower density plastic. A cantilever in the manner of an atomic force microscope (AFM) carrying 100x400x20 micron^3 rectangular gold test weights is positioned above the intermittent density surface. Upon rotation of the bearing, the test weights are subjected to periodic variations in density from which the deflections of the cantilever provide a measure of the gravitation attraction.

To avoid Casimir and electrostatic forces that usually are significant at submicron separations of the test weights, the gravitation tests are run at separations of about 10 microns. However, stray forces are still claimed to limit the test sensitivity.

Stray CP, L, and BB forces that provide a source of error in the measurement of gravitational force may be estimated by considering the force induced by a gold atom adjacent a surface. For gold having an atomic weight W = 196.96, the mass m of an atom is, m = W / N_{Avag} = 3.27×10^{-25} kg. The gravitation force F_{Grav} = m G = 3.21×10^{-24} N.

The magnitude of the CP, L, and BB forces in relation to the gravitation force for a gold atom is based on the polarizability $\alpha_o = 6.1 \times 10^{-30}$ m^3. In Fig. 4, the BB force is plotted for 300, 20, and 8 K. The L force is shown for 8 K and the CP force is independent of temperature.

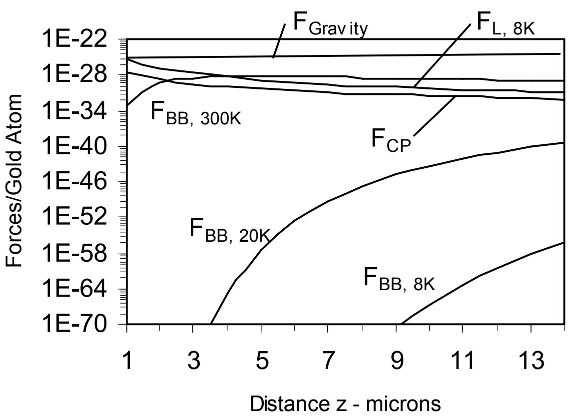

Figure 4. Stanford Gravitation Test
Forces on Gold Atom at Cryogenic Temperatures

At z = 10 microns, **a**ll forces are observed to be smaller than the gravitation force even at ambient temperature of 300 K. Unlike rubidium, gold has a 6x smaller polarizability to allow the Stanford test to be valid with regard to temperature.

What this means is the stray effects are caused by other factors. The only other mechanism that can lead to stray forces is the electrostatic charging [8] by QED induced EM radiation. However, at 10 micron separations FIR radiation at 20 microns would have to be shown to produce at least a few electrons by the photoelectric effect. Companion tests to determine the photoelectric yield of gold at cryogenic temperatures under FIR radiation at 10 microns is required.

But QED induced EM radiation may simply supply heat in the FIR to locally alter the gap between the cantilever and gold shield, instead of removing electrons.

Experiments at Stanford directed to determining the sensitivity of cantilever deflection to an external source of FIR radiation focused in the gap. Perhaps, the FIR could be simulated with the NIR laser that detects cantilever deflections.

If tests were being run at gaps of 0.1 microns, the QED induced EM radiation would occur in the VUV at 0.2 microns. But this is not the case. However, during set-up, the cantilever may contact the gold plate during calibration. If so, charge may be produced that remains during operation at gaps of 10 microns. Grounding of the cantilever prior testing is recommended to eliminate stray charges.

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