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Near-field thermal electromagnetic transport (Invited Review Talk)

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Despite the fact that the thermal radiation transport and light scattering theories seem disjointed, heat transfer by radiation is fundamentally an electromagnetic scattering and absorption problem. The only difference between radiation heat transfer and classical electromagnetic scattering is that emission of a thermal electromagnetic field is due to fluctuations of charges caused by thermal agitation. As for any electromagnetic field, the thermal field is composed of propagating and evanescent modes.

Radiative transport problems are typically simplified by using Planck's theory of heat radiation. By doing so, two physical mechanisms are omitted. First, radiation transport is treated as incoherent (rays or photons) such that wave interference is neglected. Additionally, evanescent modes, decaying exponentially within a distance of approximately a wavelength normal to the surface of a thermal source, are not accounted for. Neglecting coherent transport and the contribution of evanescent modes to heat transfer is acceptable as long as the size of the bodies and their separation distance is much larger than the thermal wavelength, which is roughly 10 μm at room temperature.

Near-field thermal electromagnetic transport refers to the case where the size of the bodies and/or their separation distance is smaller than the thermal wavelength. In this regime, Planck's theory ceases to be valid and radiation heat transfer is modeled via a phenomenological framework called fluctuational electrodynamics, where the Maxwell equations are augmented by stochastic currents representing thermal emission ("thermal stochastic Maxwell's equations"). The stochastic currents are correlated to the local temperature of the source via the fluctuation-dissipation theorem.

In this Talk, near-field thermal electromagnetic transport will be reviewed. The general electromagnetic description of thermal radiation will be presented, and the limitations of fluctuational electrodynamics will be highlighted. An important portion of the presentation will be devoted to the thermal discrete dipole approximation (T-DDA), which is a method for solving near-field thermal radiation problems in three-dimensional arbitrary geometries. In the T-DDA, objects are discretized into cubical sub-volumes conceptualized as electric point dipoles as in the "classical" discrete dipole approximation. The accuracy and the convergence of the T-DDA will be discussed by using the exact results for the two-sphere and sphere-surface configurations. Finally, the applications of near-field thermal electromagnetic transport to energy conversion and thermal spectroscopy will be overviewed.