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A billion trillion "clashes" make a plasma: averaging over the micro to understand the macro

A systematic treatment of microscopic collisions to extend fluid models of plasmas

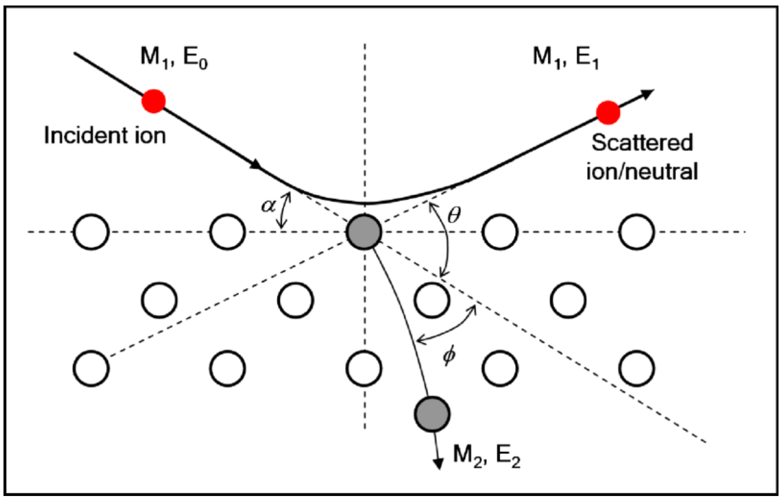

Image courtesy of the University of Warwick

At the microscopic level, binary collisions between charged particles conserve two fundamental quantities, namely momentum and energy. This conservation must be present in fluid models in order to describe the macroscopic evolution of plasmas correctly. A systematic treatment of collisional effects is presented to derive fluid models beyond the usual assumption of "thermal equilibrium". Such extended models will greatly help model and understand cold and moderate temperature plasmas as, for example, at the edge of fusion devices. Understanding and controlling the edge plasma is crucial for maintaining confinement of the ultra-hot core where the fusion reactions occur.

The Science

The collective behaviour of charged particles colliding against one another in plasmas gives rise to very rich and diverse phenomena. Perhaps most importantly, it is only through collisions that the plasma in a fusion reactor reaches a quiescent state known as "thermal" equilibrium that is free from macroscopic instabilities. The computational challenge of kinetic simulations of collective behaviour is almost overwhelming even for the most powerful computers 20 years from now because of the long-range electromagnetic force and the sheer number of particles, up to 10^{20} involved. Instead, one constructs statistical averages, or so-called fluid theories, to simplify the representation of plasmas close to thermal equilibrium. It is much easier to understand the dynamics of fluids than to understand the collective interactions of one hundred billion trillion charged particles. Averaging the almost-infinite detail of the "micro" to obtain a simple "macro" description is no easy task, particularly if one wishes to ensure that fundamental conservation laws, e.g. momentum and energy conservation, are satisfied. Researchers at

PPPL have derived a general solution to the problem of obtaining a macroscopic description of plasmas in the limit of so-called gazing collisions - where the scattering angle from a single collision is small but the large number of accumulated collisions leads to a significant deviation of the particle’s free trajectory - known as Landau’s approximation. From this approach, existing fluid models such as the widely used magnetohydrodynamics (MHD) model can be extended to include the collisional contributions of distribution functions that are not in thermal equilibrium, thereby capturing more microscopic details in the macroscopic picture.

The Impact

The main advantage of fluid models is a reduction in complexity. The rigorous treatment of collisions enables a systematic extension of the commonly used Braginskii equations to include finer details of the microscopic interactions and deviations from thermal distribution functions. Tracking the evolution of higher-order moments of plasma characteristics is **essential** to reproducing the complex collective phenomena occurring in cold and moderate temperature plasmas such as in the edge of fusion devices and in various astrophysical plasmas. The procedure can equally be applied to the study of the formation of galaxies - where the force between microscopic objects is also proportional to the inverse square of the distance.

Summary

This research shows that the statistical effect of Coulomb collisions in a plasma can be expressed exactly in terms of what are called multi-index Hermite-polynomial moments of the distribution functions. The collisional moments are shown to be generated by derivatives of two well-known functions, namely the Rosenbluth-MacDonald-Judd-Trubnikov potentials for a Gaussian distribution. The result can be applied to both the classic transport theory of plasmas, that relies on the Chapman-Enskog method, as well as to deriving collisional fluid equations that follow Grad's moment approach. As an illustrative example, we provide the collisional ten-moment equations with exact conservation laws for momentum- and energy-transfer rate.

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Publications

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