Understanding plasma flow interactions with dust and probes by simulation

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The interaction of solid objects with a plasma has been a vital part of plasma physics since its beginning. The most characteristic application is to understand how to relate the electric current/voltage characteristic of a Langmuir probe to the surrounding plasma parameters; but other vital applications include the charging and dynamics of dust particles, the interaction of space vehicles with their surrounding plasma, and the interaction of the solar wind with planetary bodies.

The long-standing classic theories are generally based upon assuming the configuration to be symmetric, e.g. spherical or cylindrical. However, in many important situations, there is substantial flow velocity of the plasma relative to the object. This flow breaks the symmetry, and therefore requires two- or three-dimensional calculations to understand the resulting asymmetry in flux to the probe, which is the basis of so-called Mach probes. Moreover, because the orbits of the attracted species (usually ions) cross each other, giving rise to highly non-Maxwellian velocity distributions, a low-collisionality plasma in the vicinity of a probe cannot reliably be represented by a fluid plasma model. Kinetic treatment is often essential. Finally, the plasma response can be highly non-linear in the sheath regions that surround immersed objects. We therefore require a six-dimensional $(\mathbf{x}, \mathbf{v})$, kinetic, non-linear treatment.

The Particle In Cell (PIC) plasma simulation approach is highly appropriate for this purpose; and we have built an electrostatic code, SCEPTIC, aimed at high-fidelity calculations of spherical objects and plasma domains, and another, COPTIC, that models cuboidal domains containing multiple objects of different shapes. Both can accommodate arbitrary strength uniform magnetic field that is vital for understanding probes in magnetic confinement devices and can include neutral collisions that are an important influence in most dusty plasma experiments. An outline of how these codes work will be given.

Examples of recent important new results from these studies will be described, such as the understanding of dust particle alignment mechanisms associated with the plasma wake as a function of flow speed. Comprehensive calculations of the drag force that the plasma exerts on embedded dust and intergrain forces. Demonstration of the strong influence of ion velocity distribution function shape on plasma wake. Validation of the calibration of Mach probes in their deduction of parallel and perpendicular drift velocities in magnetized plasmas. And the demonstration of unsteady electrostatic instabilities in Mach probe wakes.

This flowing plasma interaction topic is rich in basic plasma phenomena and important practical applications.