Hypervelocity impact plasma expansion: scaling from experiment to space

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Impacts of meteoroids and orbital debris on spacecraft and other solid bodies occur at speeds great enough to generate a dense plasma. This plasma is composed of ionized material from the impacting object and from the impacted surface, and rapidly expands under the influence of external fields. This phenomenon has been studied extensively in laboratory facilities using electrostatic dust accelerators and light gas guns to propel projectiles at speeds representative of impacts in space. However, light gas guns typically can only accelerate individual projectiles in the 1 mm to 1 cm size range, and smaller projectiles in simultaneous bursts. Light gas guns tend to be limited to speeds below 7 km/s, with some facilities achieving speeds of 10 km/s with particular projectile shapes and sizes. Electrostatic dust accelerators propel much smaller projectiles in the range of 0.02 to 5 microns, and can achieve speeds of 10 to 100 km/s with the smallest projectiles (below 0.3 microns in diameter).

Because of the limitation in ground-based experimental facilities, there is little opportunity to study the behavior of impact plasmas produced by conditions representative of meteoroids in space. Nanogram-sized meteoroids (approximately 10 microns in size) can impact Earth-orbiting spacecraft at a rate of one per square meter per day, at speeds of 11 to 72.8 km/s. We present results derived from analytical models and particle simulations to characterize how the expansion of an impact plasma can vary as a function of impactor size. The analytical model uses an energy balance of internal and external electrostatic fields for a single ion species. The plasma plume edge is assumed to have a velocity imparted perpendicular to the impacted surface by external fields, and parallel to the surface by internal fields. The initial size of this single species plasma is estimated using the electron saturation current to provide a lower bound and plasma sheath theory to provide an upper bound on when electrons are absorbed by the positively charged impact surface. This model predicts that nanogram impactors yield plumes that expand with a cone angle of 120–180˚, while the femtogram impactors that are observed in laboratory experiments yield plasma plumes with cone angles less than 10˚. This is consistent with simulation results using a tree code to model the plasma expansion.

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