

Irreversibility and Statistical Realizability in Collisionless Plasma Models

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We develop a general framework to study entropy growth in collisionless systems described by reduced moment hierarchies. Within this framework, we introduce a classification of closures into *hard* and *soft* types, depending on whether they preserve or violate exact invariants of the underlying kinetic dynamics. By constructing a closure-dependent entropy hierarchy, we show that hard (invariant) closures remain formally reversible, whereas soft (non-conservative) closures generate a residual entropy associated with irreversible loss of phase space information to unresolved kinetic scales. This residual entropy grows monotonically under broad conditions, thereby imposing a realizability constraint on admissible macroscopic states even in the absence of collisional dissipation.

Applying the framework to anisotropic collisionless plasmas, we derive the entropy production explicitly at second order and identify contributions from parallel and perpendicular transport and magnetic field inhomogeneity. The resulting entropy balance defines an exclusion region in the space of temperature anisotropy and plasma beta, corresponding to statistically inaccessible macroscopic states. For a simple illustrative soft closure, the predicted entropy exclusion boundary is broadly consistent with observed distribution of the space plasma fluctuations, despite the minimal nature of the model. These results identify statistical realizability as a complement to stability in reduced collisionless plasma models and clarify the origin of irreversibility in fluid closures.