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ABSTRACT

Although hypersonic flight was invented in the US, our technological advantage over adversaries has significantly narrowed. Development of future *hypersonic capabilities* is a challenge that requires *revolutionary advances* in many research areas; first and foremost, is the ability to accurately and efficiently model hypersonic environments, characterized by *non-equilibrium plasma flows*. This proposal outlines a new paradigm for the construction of predictive modeling and simulation tools from a *fundamental physics perspective*, rejecting the empiricism that has prevented progress in the modeling of hypersonic flows for decades. This effort will establish the first *physics-aware reduced-order model* as a modernized approach to hypersonic vehicle design, enabling the implementation of new ideas, only found in science fiction books: the ability to use magnetic fields to control plasma flows, to mitigate heating, or to use magnetic windowing to enable communication, just to name a few. This proposal will enable a new design paradigm, replacing today's over-designed hypersonic vehicles with systems going faster, farther and featuring unprecedented maneuverability.

The most physically consistent description of non-equilibrium plasma flows relies on the solution of the *Boltzmann* equations for particles and photons, coupled with the *Maxwell* equations to describe the coupling of the plasma to self-consistent electric and magnetic fields. However, for problems of interest, the exponentially large number of degrees of freedom, and the wide range of spatial and temporal scales involved, make these equations unsolvable. Inspired by model reduction strategies developed in statistical physics, this work addresses *the challenges of the combinatorial explosion of the possible configurations of the system*, obtaining new governing equations by projecting the *high-dimensional* Boltzmann equations onto a few *lower-dimensional* subspaces. The distribution function within each subspace is then reconstructed using *the Maximum Entropy Principle*, thus ensuring compliance with the *Detailed Balance.*

The systematic hierarchical coarse graining of the kinetic equations will enable the use of the novel concept of *Adaptive Mesh and Model Refinement* (AM2R) of the *Phase Space,* that allows the automatic tailoring of the model complexity as a function of the local plasma conditions.

Given its mathematical structure, this platform enables the implementation of acceleration strategies based on *physics-informed learning*. The success of these techniques relies on the availability of data, in the form of high-fidelity simulations, here provided by the Coarse-Grained model, and on the use of governing equations as a constraint of the surrogate. For the first time, this model will capture strong deviations from equilibrium, across continuum and rarefied regimes, for both internal and translational degrees of freedom in the gas, providing a unified and physically consistent description of the non-equilibrium phenomena.

In summary, this approach has the potential to revolutionize the computation of high-enthalpy flows with non-equilibrium thermo-chemistry and rarefaction effects by providing a prototyping tool able to replace the kinetic equations with a reduced-order model, preserving the essential properties of the original one, but many orders of magnitude faster.

The proposed work will provide a transformative capability for fundamental hypersonic research, serving as a centerpiece for the *Center for Hypersonics and Entry Systems Studies* (CHESS), *stood up* and *directed by* the PI. This synergy between the VBFF (i.e., DoD) and CHESS will amplify the impact of the research achieved, creating a truly unique ecosystem for fundamental hypersonic research.