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Project Name: Collaborative Research: Vlasov-Maxwell Simulations to Resolve Electron Heating and Dissipation, in Quasi-Perpendicular Shocks

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1.0 Major Goals of Project The major goals of the project are to study three fundamental questions related to collisionless, non-relativistic, quasi-perpendicular shocks by combining continuum Vlasov-Maxwell simulations (the Gkeyll framework) and high resolution, in situ heliospheric observations from the MMS spacecraft. The specific questions are:

1. How and where are electrons energized and heated in a quasi-perpendicular shock, including the ultimate source of entropy production?

2. What role do waves, turbulence, and secondary instabilities play in the conversion of directed flow energy to electron energy?

3. How do the parameters of the shock determine the energization of electrons?

2.0 What was accomplished under these goals? During this project, the entire team, combining members from the University of Arizona, Princeton, and the University of Maryland has focused on each of the overall goals. Extensions to previous applications of the field-particle correlation method, an analysis method developed by PI's Klein and TenBarge to determine which electrons with what velocities or pitch angles are being heated or accelerated, to additional shock simulations beyond those described in Juno et al 2021[1]. This was written up for publication in [2]. These newer results consider additional shock parameters beyond the 1D-2V simulation that were used in the previous paper.

By applying the field-particle correlation, alongside additional analysis methods, to the high fidelity representation of the particle distribution function provided by a direct discretization of the Vlasov equation, rather than the typical PIC methodology, we have been able to characterize details of the exchange of energy between the electromagnetic fields and the particles as a function of both position and velocity, leading to the identification of the specific signatures of shock-drift acceleration. These energization signatures compare favorably to analytic predictions. The additional simulation runs under analysis will specifically address the third question by determining which parameters govern essential elements of the shock energization process.

PI Klein has also worked with PI TenBarge to extend the linear Nyquist instability identification method to better address the second science question. The extensions are for the particular geometries and observed velocity distributions—e.g. a bi-kappa distribution instead of a bi-Maxwellian distribution— associated with kinetic instabilities observed at shocks, e.g. the electron-cyclotron drift instability. These linear calculations provide a set of initial conditions for studying the nonlinear saturation of these instabilities using Gkeyll simulations. This work was presented at the Fall 2022 APS-DPP meeting. These same analysis tools were used for a study of unstable waves measured by MMS [3], in which the non-Maxwellian structure of the electron distribution function interacting with kinetic processes lead to the generation of unstable waves.

3.0 What opportunities for training and professional development has the project provided? The project provides the opportunity for training one of the PIs as a postdoc to analyze in situ spacecraft measurements and conduct research on collisionless shocks.

4.0 How have results been disseminated to communities of interest? The current results of the research have been presented in the form of several presentations in virtual and hybrid formats at national conferences and published in peer-reviewed journals.

In addition to the above mentioned papers, an additional paper that uses insights from our studies of shocks to motivate future spacecraft and in situ observatory designs [4] has been published acknowledging the support of this project.

Elements of these results, acknowledging the support of this grant, were presented at SHINE, AGU, and APS-DPP by the Co-PI's on the associated collaborative grants. Publications with PI Klein as a co-author supported by this grant have accumulated 28 citations thus far in peer-reviewed publications.

5.0 Impact

5.1 What is the impact on the development of the principal discipline(s) of the project? Weakly collisional, magnetized shocks are ubiquitous in the universe, and this project advances the understanding of how particles are energized and thermalized in heliospheric shocks, and in particular what role instabilities play in mediating this energy transfer. This work directly benefits the space and astrophysics communities by better explaining the physics of shocks.

5.2 What is the impact on other disciplines? Shocks are a fundamental physical process, arising in any fluid system where the flow transitions across a characteristic speed, making the research project of broad interest and applicability to space, astrophysical, and laboratory plasma physicists. Many astrophysical quasi-perpendicular shocks have similar parameters to those in this study, including supernova remnants and the intracluster medium.

Lastly, the simulation code, Gkeyll, and associated analysis scripts are openly available for community use.

5.3 What is the impact on the development of human resources? Nothing to Report

5.4. What is the impact on physical, institutional, and information resources that form infrastructure? Nothing to Report

5.5. What is the impact on technology transfer? Nothing to Report

5.6. What is the impact on society beyond science and technology? Nothing to Report

5.7. Foreign Spending Nothing to Report

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