Title: Heat flux closures for relativistic two-fluid/Maxwell systems in collisionless plasmas

Sector of research: Dr. rer. nat.

Degree awarded: Theoretical Physics

Keywords: reconnection, collisionless plasmas, Vlasov equation, two-fluid/Maxwell system, MHD

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Research focus of supervisor: The main interests of TP I are, on the one side, the development of multiphysics/multiscale simulations of collisionless plasmas and, on the other side, the understanding of intermittency in turbulent fluids and plasmas using non-perturbative methods. The first topic is the focus of this dissertation. This topic addresses the occurrence of multiple temporal and spatial scales in collisionless fusion, space, and astrophysical plasmas, which require different physical models at different spatial and temporal scales. These models range from magnetohydrodynamics/Ohm’s law (on large scales), two fluids/Maxwell to a kinetic description using the Vlasov/Maxwell system. The specialty of our group is the development of multiphysics/multiscale simulations that adaptively decide in which spatial region which model is appropriate, as well as coupled simulations of these different models. Massive parallel HPC simulations are performed on clusters of GPUs.

Publications:
1. F. Allmann-Rahn, S. Lautenbach, R. Grauer, and R. D. Sydora, JPP 87 (2021) 905870115

Summary of research plan

Background: Motivation and State-of-the-art: One of the main challenges in astrophysical, space and fusion plasmas is the treatment of different spatial and temporal scales and the correct physical description on each of these different scales. To give a rough estimate for different plasma systems, consider the warm ionized phase (diffusely ionized hydrogen) in the interstellar medium. Here the smallest relevant kinetic scales are in the order of kilometers, while the global scale of the system is about 10^{13} km. In the heliosphere the scales are smaller overall (kinetic scales about 2 km, system scale about 10^{8} km), but the ratio of global to kinetic scales is still astronomical in the truest sense of the word. The situation is similar for fusion plasmas: the electron skin depth is about 0.0005 m and the vessel measures about 10 meters. In all these cases it is not possible to perform simulations that represent all scales with
the finest level (kinetic equations) of physical description. Such collisionless plasmas can be modelled with the kinetic Vlasov equation. Nevertheless, kinetic models are inherently computationally expensive, so that large-scale simulations of typical phenomena, as for example magnetic reconnection or collisionless shocks, are hardly feasible and only possible in localized regions of interest. As an alternative, much cheaper fluid models can be considered, but they lack the expressiveness and some physics of full of kinetic models.

Our group has made significant progress in the development and application of a Landau damping motivated heat flux closure that is able to bridge to the kinetic regime. These considerations so far were developed for applications in space plasmas. The extension of a heat flux closure to the special relativistic regime necessary to describe reconnection in astrophysical jets is the subject of this thesis.

**Study objective:** The primary objective is to develop a relativistic covariant heat flux closure to be applied to various reconnection scenarios in astrophysical plasmas. In this thesis, analytical and numerical work is combined to extend existing models for relativistic resistive MHD descriptions to the 10 moment/two fluid case. These will be tested in various environments ranging from mildly relativistic regimes (which should approximate the situation in space plasma) to highly relativistic jets to understand plasmoid formation triggered on kinetic scales.

**Expected Results:** The aim of this work is to obtain a more detailed understanding of reconnection in the relativistic domain. Particularly important are questions about the importance of the rest mass ratio of electrons to ions and its effects on instabilities such as firehose and LHDI. In addition, implications for a generalized Ohm's law are analyzed. Publications are planned on the various phases of the analytical and numerical studies.

**Methods:** Both analytical and numerical methods are used. Analytical methods include kinetic theory, Landau damping, covariant formulations of kinetic and fluid systems, heat flux closures. Numerical methods include structure preserving finite volume schemes, Maxwell solvers, HPC (MPI and CUDA). A cluster of GPUs is available at the institute. Production runs are performed at the HPC centre of the FZ Jülich.

**Candidate Requirements:** MSc degree in Theoretical Physics or Applied Mathematics, basic knowledge of plasma physics including kinetic theory; experience with programming languages and coding; sound knowledge of English.

**Motivation for CSC application:** You will work on a truly challenging plasma-astrophysical problem in an international environment. Here, I would like to emphasize at this point that my role as mentor of young scientists is reflected in the fact that 11 of my former students are now professors or in comparable research positions. In addition, locally you will be integrated in the Ruhr University Research School, for interdisciplinary skills development.