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Kinetic Landau-Fluid Closures of Non-Maxwellian distributions

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Non-Maxwellian plasmas are in fact fairly common in the laboratory, space, and astrophysical environment, and yet most of the theoretical studies so far on heat flux closure are performed under the near-Maxwellian assumption. Inspired by the non-Maxwellian particle distribution phenomenon, e.g., in the SOL of tokamak plasma and inverse bremsstrahlung heating in laser-plasma, new kinetic Landau-fluid closures are derived for non-Maxwellian distribution plasmas in this work.

A special static case (i.e., zero mode frequency) is first considered for plasmas with cutoff Maxwellian distribution. In the strongly collisional regime, this model reduces to Braginskii's local heat flux model[1]; while in the weak collisional regime, the heat flux becomes non-local and recovers the Hammett–Perkins model[2] when the value of the cutoff velocity approaches infinity. Comparison of the thermal transport coefficient χ for Maxwellian, cutoff Maxwellian, and super-Gaussian distributions shows that the reduction of the high-speed tail particles leads to the corresponding reduction of the thermal transport coefficient χ across the entire range of collisionality, more reduction of the free streaming transport toward the weak collisional regime. In the collisionless limit, χ approaches zero for the cutoff Maxwellian and the super-Gaussian distribution but remains finite for Maxwellian distribution. Interestingly, χ is complex if the cutoff Maxwellian distribution is asymmetric, and $\mathrm{Im}(\chi)$ yields an additional streaming heat flux in comparison with the symmetric cutoff Maxwellian distribution. In addition, there is a background heat flux q_0 for asymmetric cutoff Maxwellian distribution. The heat flowing-up temperature gradient is found in the weak collision regime $\nu_c/\sqrt{2}V_T|k| \ll 1$ when the lower cutoff velocity is small enough for asymmetric cutoff Maxwellian distributions, as shown in because particles flowing from low to high temperature dominates those from the opposite direction, the net heat flux flows up the temperature gradient.

The derived Landau-fluid closures are general for fluid moment models, and applicable for the cutoff Maxwellian distribution in an open magnetic field line region, such as the scape-off-layer plasmas, the thermal quench plasmas during a tokamak disruption, and the solar corona, and the super-Gaussian electron distribution function[3] due to inverse bremsstrahlung heating in laser-plasma studies. The kinetic closure is a complex function with both frequency and wave vectors in Fourier space. Implementing such a Landau-fluid closure to high-performance fluid codes is numerically challenging. Riding on the rapid development of machine learning (ML) and following on our previous work[4] developing ML surrogate closure model for accurate and efficient fluid moment simulations will be our future work.

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