Influence of Nonextensivity on Current Density and Sheath Structure in Warm Ion Plasmas

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This work models a plasma with nonextensive electrons and warm ions using hydrodynamic equations and numerically solves the governing system. The effect of the nonextensivity parameter q on current density and sheath properties is investigated. Results show that a higher q increases the charged-particle current within the sheath, while the interface current remains nearly unchanged. Additionally, the sheath thickness decreases as q increases.

1.) *Introduction*

Numerous studies have explored plasma sheath dynamics and the factors influencing particle interactions in this region[1,2]. Recent findings suggest that Gibbs–Boltzmann statistics are inadequate for systems with long-range interactions like Coulomb forces in plasmas[3,4]. Consequently, non-extensive Tsallis statistics have increasingly been adopted to analyze plasma behavior.

2.) Basic Equations

Using the fluid equations, the normalized basic equations of the plasma sheath in a plasma with ions and Tsallis electrons are as follows [1,4,5]:

$$(1 - T/u_x^2)\, u_x\, u_x' = \varphi'$$

$$\varphi'' = M/u_x - N_e$$

where the prime symbol means d/dX, and the normalized electron densities is:

$$N_e = (1 - (q_c - 1)\phi)^{(q_c + 1)/2(q_c - 1)}.$$

Additionally, the normalized charged-particle current density for an ion–electron plasma is defined as follows:

$$J = J_i - J_e = N_i\, u_x - (m_i / 2\pi\, m_e)^{1/2} N_e$$

As observed, the normalized current density of charged particles in the sheath region depends on the ion velocity and the electron and ion densities within the sheath. These quantities, in turn, depend on the plasma nonextensivity index (q). By numerically solving the main equations of the presented model, this dependence is examined in more detail. To carry out this analysis and compute the ion velocity and density inside the sheath and at the wall of such a plasma, the fourth-order Runge–Kutta method is employed to solve basic equations. In addition, the quasineutrality condition, zero electrostatic potential, and negligibly small electric field at the sheath edge are imposed as boundary conditions.

3.) Numerical Results and discussions

In Fig. 1, the behavior of the normalized current density of charged particles is plotted as a function of distance from the sheath edge for different values of the plasma nonextensivity index (q). As observed, increasing q leads to an increase in the current density inside the sheath region (i.e., its negative value decreases), and the curve approaches the saturation level with a steeper slope.

In other words, since in the limit q→1 the nonextensive distribution reduces to the Boltzmann distribution, it can be stated that for q<1, the closer the plasma approaches thermodynamic equilibrium, the greater the normalized current density becomes, whereas for q>1, approaching equilibrium leads to a reduction in this quantity.

To understand this behavior, we examine the nonextensive distribution function versus normalized velocity for different values of q. As is known, by decreasing q, the number of high-energy electrons located in the tail of the distribution function increases. Therefore, the electron flux —and consequently the electron current— decreases as q increases, which results in a more positive total current density (i.e., a reduction in its negative magnitude).

Furthermore, Fig. 1 shows that the value of q has no effect on the current density at the sheath edge. Also, as seen in this figure, with increasing q, the current density reaches zero at a shorter distance from the sheath edge, which can be interpreted as a reduction in sheath thickness with increasing q.

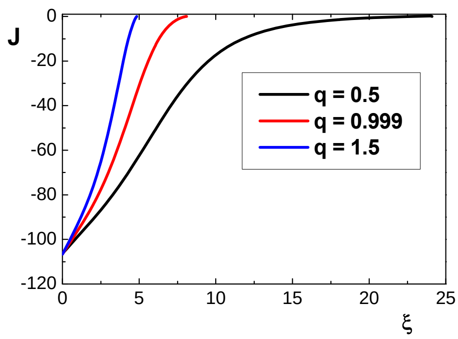

Fig. 1: Variation of normalized current density with q index.

4.) Conclusion

In this study, we modeled a quasi-neutral ion–electron plasma consisting of warm ions and electrons described by the Tsallis distribution. Numerical analysis of the governing equations reveals a distinct dependence of the sheath current density on the nonextensivity index (q). Specifically, when (q<1), approaching thermodynamic equilibrium (i.e., q→1) results in an increase in the sheath current density. In contrast, for (q > 1), the current density decreases as the plasma tends toward equilibrium.

5.) References

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