Non-extensive thermodynamics of partially ionized gas in magnetic field

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Thermodynamics is a fundamental science with strict physical laws for changes of state, and deals with energy, heat, work, entropy, and spontaneity of processes. The laws of thermodynamics are a universal theoretical system that indicate the transitivity of thermal equilibrium, energy conservation, irreversibility of thermal phenomena, and absolute zero point of a thermally equilibrated system. Importantly, thermodynamics defines the physical parameters of an ionized gas and is combined with local or non-local equilibrium theory to understand the complex physics of such a system.

Contrary to classical thermodynamics, which deals with systems in thermal equilibrium, ionized gases generally do not reach thermal equilibrium among all particle species or within each particle species in a volume. In particular, non-Maxwellian electron distributions are observed in space plasmas [1], which are essentially collisionless systems. As a result, stationary states of ionized gases out of equilibrium are not readily understood through classical statistical descriptions of thermal equilibria.

Classical thermodynamics has evolved to include partially ionized gas systems that are not in equilibrium and to explain their physical properties. The field of non-extensive statistical mechanics pioneered by Tsallis generalizes the thermodynamic laws of non-equilibrium systems [2]. Under statistical mechanics, the non-Maxwellian distribution observed in a space plasma is valid for entropy and other relevant thermodynamic properties. Most importantly, the ability to independently observe temperature and entropy enables numerous analyses on phenomena such as turbulence. Non-extensive statistical mechanics is currently essential to our understanding of non-equilibrium astrophysical plasmas.

The laws of physics have been accepted as established and universally valid through rigorous empirical verification, and the laws of thermodynamics are being completed through measurement and observation of variables in a statistical context from the Joule paddle-wheel and Stirling engine to black holes. In plasma thermodynamics, the magnetic nozzle is used to analyze astrophysical phenomena because they share fundamental plasma physics such as non-Maxwellian electron energy distributions in collision-free conditions [3]. However, although a magnetic-nozzle plasma experiment well reproduces the space plasma environment, thermodynamic laws have only been verified under the assumption of classical thermal equilibrium.

Here, we verify the thermodynamic laws of reversible and adiabatic processes for a magnetically expanding ionized gas. Together with the experimental evidence of the non-Maxwellian electron distribution, the kappa distribution, which measures the thermal equilibrium states, shows the Tsallis entropy to be nearly constant and the polytropic index to be close to adiabatic values along a divergent magnetic field. These results verify that the collisionless magnetic expansion of a non-equilibrium plasma is reversible and adiabatic, and an isentropic process is the origin of the high-energy tail of the energy distribution far downstream.

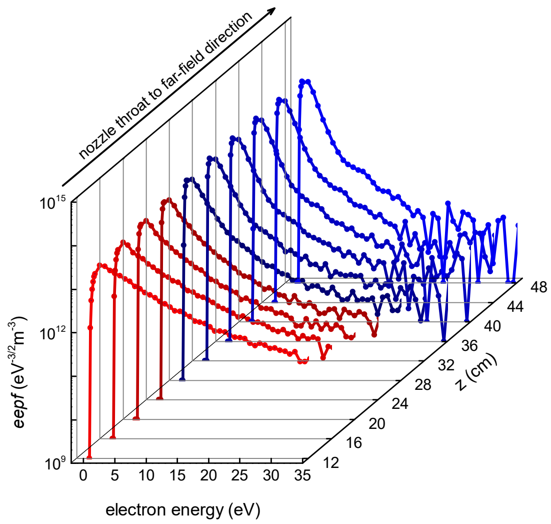

Figure 1. Axial evolution of *eepf*s at different axial positions (12 to 48 cm from the nozzle throat at intervals of 4 cm). The deviation from a Maxwellian energy distribution is greater approaching the far downstream region, where a heavy high-energy tail above 5 eV develops.

References
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