Temperature and its uncertainty in nonequilibrium steady state plasmas

Sergio Davis
Comision Chilena De Energia Nuclear, Santiago, Chile

The concept of temperature, which is precisely defined only for thermal equilibrium states and in systems with short-range interactions, lacks such a foundation in the case of nonequilibrium steady states. This issue is believed to be at the core of the striking effects occuring in complex systems with long-range interactions (such as space plasmas and laboratory plasmas, as well as in self-gravitating systems). Due to the long-range correlations present in these systems it is no longer possible to speak of independent, uncorrelated regions, and the presence of correlations between different regions of a system can introduce temperature fluctuations even in macroscopic systems. This issue has led to the idea of superstatistics. Superstatistics [1] is a nonequilibrium framework, an alternative to Tsallis nonextensive statistics, that assumes a superposition of equilibrium models at different temperatures and aims to describe steady states having power laws instead of the usual Boltzmann-Gibbs statistics. Despite the success and clarity of the superstatistical framework, the conceptual meaning of temperature in nonequilibrium steady states still remains to be clarified, and this provides an open challenge for the statistical mechanics community.

In this work, we first provide a brief review of the main ideas behind the theory of superstatistics, and why it appears to be an attractive alternative to the framework of Tsallis nonextensive statistics in the context of nonequilibrium plasmas. In particular, we put our focus on plasmas having a kappa distribution of velocities, which is the generalization of the Maxwell-Boltzmann distribution within the Tsallis framework. Our main result is the derivation of the kappa distribution from first principles, using only the framework of superstatistics and one simple requirement on the correlation between the kinetic energy of a test particle and that of its surrounding environment. The corresponding inverse temperature distribution is the gamma distribution, which is referred to as the chi-squared superstatistics, and we show the connection between this inverse temperature distribution and the distribution of the fundamental inverse temperature [2], a property of the steady-state statistical ensemble.

References

[1] C. Beck, E. G. D. Cohen, Physica A, 322, 267-275 (2003).
[2] S. Davis, G. Gutiérrez, Physica A, 533, 122031 (2019).