Kappa distributions: Theory and connection to thermodynamics

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Kappa distributions have become increasingly widespread in Space Physics as the power-law nature of various suprathermal tails is merged with the classical Maxwellian cores. Kappa distributions are frequently used to describe particle populations in the heliosphere, from solar wind and planetary magnetospheres to the heliosheath and beyond, the interstellar and intergalactic plasmas. Recent theoretical developments explain the origin of kappa distributions through statistical mechanics and thermodynamics, revealing the robust physical meaning of temperature and kappa that parameterize these distributions. These have been shown to be involved in numerous space plasma properties and processes, e.g., polytropic expansion, particle acceleration and circulation; pickup ions; plasma instabilities, etc. Here we review the recent developments in regards to the theory of kappa distributions and its thermodynamic origin: (1) Kappa distributions maximize the entropy of nonextensive statistical mechanics under the constraints of canonical ensemble; (2) Systems exchanging heat with each other and reaching thermodynamic equilibrium are stabilized always into the formulation of kappa distributions; (3) Polytropic flows are uniquely consistent to kappa distributions and their statistical formalism; and (4) The concept of entropy defect, that is, the decrease of entropy due to long-range correlations among the constituents is one-to-one consistent with the formulation of kappa distributions.

References

[1] G. Livadiotis, D.J. McComas, Beyond kappa distributions: Exploiting Tsallis statistical mechanics in space plasmas, J. Geophys. Res., 114, A11105 (2009).
[2] G. Livadiotis, D.J. McComas, Understanding kappa distributions: A toolbox for space science and astrophysics, Space Sci. Rev., 75, 183–214 (2013).
[3] G. Livadiotis, Statistical background and properties of kappa distributions in space plasmas, J. Geophys. Res., 120, 1607–1619 (2015).
[4] G. Livadiotis, Kappa distributions: Theory and applications in plasmas, (Elsevier, Netherlands, UK, USA, 2017).
[5] G. Livadiotis, M.I. Desai, L.B. Wilson III, Generation of kappa distributions in solar wind at 1 AU, Astrophys. J., 853, 142 (2018).
[6] G. Livadiotis, Thermodynamic origin of kappa distributions, Europhys. Lett., 122, 50001 (2018).
[7] G. Livadiotis, On the origin of polytropic behavior in space and astrophysical plasmas, Astrophys. J., 874, 10 (2019).
[8] G. Livadiotis, Polytropes in plasmas described by kappa distributions – Application in atmospheric modeling, Contrib. Plasm. Phys., 60, e202000041 (2020).
[9] G. Livadiotis, D.J. McComas, Thermodynamic definitions of temperature and kappa and introduction of the entropy defect, Entropy, 23, 1683 (2021).
[10] G. Livadiotis, D.J. McComas, Physical correlations lead to kappa distributions, Astrophys. J., 940, 83 (2022).