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Statistical physics and thermodynamics of space and astrophysical plasmas

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Classical collisional particle systems residing in thermal equilibrium have their particle velocity/energy distribution function stabilized into a Maxwell-Boltzmann distribution. On the contrary, astrophysical plasmas are collisionless particle systems residing in stationary states characterized by the so-called kappa distribution function. Empirical kappa distributions have become increasingly widespread across the physics of astrophysical plasma processes, describing particles in the heliosphere, from the solar wind and planetary magnetospheres to the heliosheath and beyond, the interstellar and intergalactic plasmas. However, a breakthrough in the field came with the connection of kappa distributions with statistical physics and thermodynamics. Here we present the statistical origin of these distributions by maximizing the entropy in the canonical ensemble. Moreover, we show their thermodynamic origin from first principles: using only the zeroth law of thermodynamics, we derive the most generalized form of particle distribution function assigned with a temperature, that is, the kappa distributions. Therefore, two particle systems in contact that can exchange heat with each other are eventually stabilized into a stationary state that is not generally described by a Maxwell-Boltzmann, but a kappa distribution function. Finally, we summarize the penetration and incorporation of kappa distributions involvements into astrophysics and space science.

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