Why is the kappa distribution of fundamental importance in astrophysical and space plasmas?

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Goal of this white paper

This white paper addresses the importance of kappa distributions and their statistical framework of "non-extensive statistical mechanics", in order to improve our understanding of the physical underpinnings of astrophysical and space plasmas. The goal of this paper is to encourage the funding for relevant research analyses, related either to the theory, simulations, and/or applications of kappa distributions, to be more effective and frequent.

Importance of kappa distributions

Statistical Mechanics is used to determine how a particle system behaves when it resides at thermal equilibrium - the concept that any flow of heat (thermal conduction, thermal radiation) is in balance. When a particle system is at thermal equilibrium (typical behavior of earthy gases, e.g., the air), the particles are distributed in a very specific way: There are many particles with small velocities and very few with large velocities. It is possible to write a mathematical equation describing how many particles are found at each velocity; this mathematical expression is called a "Maxwellian distribution". However, space plasmas are particle systems distributed such that there are more high velocity particles than there should be if the space plasma were in equilibrium. The mathematical equation that is used to describe the space plasma is called a "kappa distribution" [1,2].

Space plasmas are better described by the generalized formula of a kappa distribution rather than a Maxwellian, where the higher velocity particles are well-described when kappa has some finite small value. In general, the larger the kappa parameter, the closer the plasma is to thermal equilibrium. When the kappa parameter reaches infinity, the plasma is exactly at thermal equilibrium and the distribution of space plasma is reduced to a Maxwellian. In this way, the kappa parameter is a novel thermal observable (like temperature, density, pressure, etc.) which can tell us about the "thermodynamic distance" of a system from thermal equilibrium [3].

The classical Statistical Mechanics has stood the test of time for describing Earthy systems which reside at thermal equilibrium and are aligned with Maxwellian distributions. Space plasmas from the solar wind to planetary magnetospheres and the outer heliosphere are systems out of thermal equilibrium, described by kappa (rather than Maxwellian) distributions, which are connected with a more general statistical framework, called "non-extensive statistical mechanics" [4].

Progress of kappa distributions

Kappa distributions have become increasingly widespread across space plasma physics with the publication rate following an ongoing exponential growth. A breakthrough in the field came with the connection of kappa distributions with the statistical framework of non-extensive statistical mechanics [1], a

solid generalization of the classical Boltzmann-Maxwell theory. Thereafter, numerous analyses have been developed; among others, are the following: (i) Theoretical understanding and derivation of thermodynamic quantities (e.g., entropy, temperature, pressure, kappa) [5,6]; (ii) Use of the potential energy into the kappa distribution, and thus, derivation of the kappa distribution of positions [7]; (iii) Development of the kappa distribution for multiple particles and degrees of freedom [8]. In addition, kappa distributions have been used to examine their effect in a plethora of plasma processes (e.g., linear/nonlinear waves, instabilities, shocks, etc) [9-12]. Also, they have been employed in a plethora of applications in space and astrophysical plasmas, throughout the heliosphere and beyond [13,14].

Scientific Questions related to kappa distributions

We conclude this white paper, presenting five sets of critical scientific questions related to kappa distributions and their implications/applications in astrophysical/space plasmas.

(1) Kappa distributions and statistical framework:

What is the connection of kappa distributions with statistical mechanics? What is the formula of the entropy for particles described by kappa distributions? What are the implications into thermodynamics?

(2) Formulations of kappa distributions:

What is the anisotropy in velocity kappa distributions, its cause, and applications? What are the formulae of kappa distributions for various plasma analyses?

(3) Origin of kappa distributions:

What are the possible realistic mechanisms, responsible for generating kappa distributions in astrophysical and space plasmas?

(4) Effect of kappa distribution in plasma processes:

What is the effect of kappa distributions on the linear plasma waves, the nonlinear wave-particle interactions, the solitary waves, on the shock instabilities, on the dusty plasma waves?

(5) Applications of kappa distributions in astrophysical and space plasmas

What are the features of the ion/electron kappa distributions in space plasmas? How these vary from the solar wind to the planetary and cometary magnetospheres? What are the implications of kappa distributions in the space plasmas beyond the heliosphere, e.g., stellar atmospheres, astrophysical nebulae, etc.?

Selected References

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