

Heavy tails in astrophysics

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What causes the heavy tails observed in measured probability density functions in astrophysical plasmas? Why are kappa distributions, or equivalently q-Gaussians, relevant? We propose there is a combination of reasons for that. One of the possible processes involved in creating heavy tails is a superstatistics. The superstatistics concept was introduced some 23 years ago [1], it applies to complex driven nonequilibrium systems that exhibit time scale separation. Typically, in a superstatistical system there is a parameter that fluctuates on a long time scale, for example the inverse temperature. If the inverse temperature is chi-square distributed, then it is easy to show that the resulting marginal distributions for the velocity of a test particle in this environment are kappa distributions (called q-Gaussians in the nonextensive community). But other types of inverse temperature distributions can be considered, for example lognormal distributions, which generate lognormal superstatistics. I will discuss as a typical example for the latter superstatistical behaviour in Lagrangian turbulence [2]. Here it is the fluctuating energy dissipation in the turbulent flow that leads to heavy tails for the marginal velocity distributions.

However, superstatistics can also arise in different ways, simply by sampling events that happen at different local temperature. Cosmic rays are an example where such a mechanism seems to be at work [3]. It is well-known that cosmic ray energy spectra exhibit power law distributions over many orders of magnitude that are very well described by the predictions of q-generalized statistical mechanics, based on a q-generalized Hagedorn theory for transverse momentum spectra and hard QCD scattering processes. QCD at largest center of mass energies predicts the entropic index to be $q=13/11$. If time remains I will go into a bit more detail of the theory presented in [3]. I will show that the escort duality of the nonextensive thermodynamic formalism predicts an energy split of the effective average temperature describing the cosmic ray spectra (which is, up to numerical factors of $O(1)$, the Hagedorn temperature). Linear combinations of the escort and non-escort q-generalized canonical distributions yield excellent agreement with the measured AMS-02 data in the entire energy range.

References:

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- [3] G.C. Yalcin and C. Beck, Generalized statistical mechanics of cosmic rays: Application to positron-electron spectral indices, *Scientific Reports* 8, 1764 (2018).