Kappa distribution as a description of spectrum of supra-thermal particles at collisionless shocks

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The departure of particle spectra from the Maxwellian is commonly observed in space plasmas, from Solar wind and Earth's bow shocks to strong collisionless shocks of supernova remnants. The similar departure is observed in kinetic particle-in-cell simulations of quasi-parallel collisionless shocks where particle distribution can be is described as a composite of thermal, supra-thermal, and non-thermal particles, the latter being accelerated in the process of diffusive shock acceleration. The supra-thermal particles are usually considered as being pre-accelerated and are treated in a similar fashion as non-thermal particles, just performing fewer diffusive shock acceleration or shock-drift acceleration cycles and having different escape probability. Describing supra-thermal and non-thermal parts as a single distribution is the basis for the so-called minimal model. However, we show that the thermal and supra-thermal parts can be alternatively described and adequately fitted with a single continuous quasi-thermal distribution – the kappa distribution, common to out-of-equilibrium astrophysical plasmas. We find that the index kappa increases with the distance from the shock, and probably over time, leading to the disappearance of supra-thermal part as lower energy particles tend to equilibrium, leaving only Maxwell's plus non-thermal distribution far downstream from the shock. Nevertheless, supra-thermal particles remain clearly present in the vicinity of the shock, at least at early times. We discuss the consequences of this for the injection of particles into diffusive shock acceleration process, assuming that non-thermal distribution, instead of Maxwellian, matches kappa distribution at some injection momentum.