Non-equilibrium statistical mechanics in relativistic plasma turbulence

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Collisionless plasmas are an ideal classical environment for exploring the principles of non-equilibrium statistical mechanics. There are many irreversible processes that can dissipate energy in a plasma, such as magnetic reconnection and shocks; in this talk, I will focus on turbulence in the relativistic regime, where the particle velocities can be close to the speed of light. Turbulence can energize the plasma toward a broad variety of possible nonthermal states, with the outcome depending on the physical parameters (such as the plasma beta, amplitude of fluctuations, or temperature relative to rest mass energy) and large-scale configuration (including driving mechanism). Particle-in-cell (PIC) simulations give detailed numerical guidance into the nature of relativistic plasma turbulence. In particular, PIC simulations give strong evidence that particle energy distributions have universal features. For example, they are often well-represented by kappa distributions, which are characterized by power-law tails that extend to the maximum energy imposed by the system domain size. Determining the quantitative properties of these particle distributions (such as the power-law index and location of the peak) is an important theoretical problem. I will describe ongoing efforts to understand energy dissipation in relativistic plasma turbulence, based on approaches from both kinetic theory and non-equilibrium statistical mechanics. In particular, I will describe recent results from two-dimensional shock-mediated turbulence, which I will argue may be a reasonable "minimal" setup for studying energy dissipation and entropy production in a collisionless plasma. PIC simulations of two-dimensional shock-mediated turbulence demonstrate efficient nonthermal particle acceleration, similar to the more complicated three-dimensional magnetized turbulence problem. These simulations exhibit rich structure including secondary Kelvin-Helmholtz and Richtmyer-Meshkov instabilities. I will describe attempts at kinetic modeling of the particle acceleration process, based on the cyclic interactions between particles and shocks. I will also mention how the results may change when the driving is adjusted, so that the turbulence becomes dominated by solenoidal motions or by fast magnetosonic waves. The results of this work has applications to modeling emission from high-energy astrophysical systems, such as neutron star magnetospheres, black-hole accretion flows, and jets from active galactic nuclei. More fundamentally, this research may test paradigms for non-equilibrium statistical mechanics.