Exploiting dusty plasma to test theories of statistical physics

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Statistical physics is largely only a theoretical area of physics. Experimental tests of these theories are uncommon due to a lack of experimental methods, especially for tracking the motion of individual atoms or molecules, in a sample. Particle tracking, however, is possible in dusty plasma experiments, making them particularly well suited for statistical-physics experiments.

Dusty plasma, which is sometimes called a fine-particle plasma or a complex plasma, consists of small particles of solid matter mixed into a usual plasma of electrons, ions and gas. The solid particles are often called dust, because this term has long been used in astronomy to describe the solid component of the interstellar medium.

Laboratory experiments start by preparing a glow-discharge plasma. Using argon at a pressure of typically 1 Pa, low-power radio-frequency voltage is capacitively coupled to a lower electrode, sustaining a plasma that has a substantial sheath just above the powered electrode.

Then, a powder consisting of polymer microspheres is introduced into this glow-discharge plasma, and the individual microspheres float to a negative surface potential, due to collecting more electrons than ions. In this way, the microspheres develop a substantial negative charge of typically 15,000*e*, for an 8-μm diameter microsphere. This large charge allows the levitation of microspheres in the electric sheath above the powered electrode. Due to the intense inter-particle Coulomb repulsion, the microspheres tend to self-organize in a Wigner lattice. This crystal can be prepared so that it consists of only a single monolayer, i.e, a 2D configuration, which is ideal for imaging.

As a crucial part of doing statistical physics experiments, the microspheres are imaged, using video cameras. Image analysis software then allows the experimenter to obtain the *x*-*y* coordinates of each microsphere, in each video frame. The velocity of individual microsphere can also be obtained, simply by subtracting positions in consecutive frames. In this way, the experiment yields phase-space data for the individual charged particles, in the form of their positions and velocities at each time. Such phase-space data at the particle level are not possible for other kinds of plasmas.

Having data for the positions and velocities of individual particles, the experimenter can use binning to convert that data into the continuum paradigm, if desired, yielding hydrodynamic quantities such as number density, flow velocity, kinetic temperature, and gradients in those quantities.

Several theories of nonequilibrium statistical physics have been tested by our experimental group, using these methods. These theories include the Stokes-Einstein relation,[1] a theory relating superdiffusion to non-Gaussian statistics,[2] the Green-Kubo relation for viscosity,[3] and the Fluctuation Theorem for a shear flow.[4]

In this talk, I will focus on the Fluctuation Theorem test, as an example of this experimental approach. This theory predicts a stochastic variation in the entropy production rate, i.e., fluctuations in the heat generated by viscous heating. While the entropy production is a positive quantity for a large sample size and a long observation time, it is possible for the entropy generation to fluctuate to negative values, for small sizes and short times. These fluctuations, to negative values of entropy production rate, are sometimes described as violations of the Second Law.

In an experiment,[4] we used laser heating to melt a crystal to sustain liquid-like conditions, and we further used laser manipulation to generate the nonequilibrium conditions of a shear flow. Within this shear flow, we calculated the entropy production rate, with an input of particle-level data from the video imaging. A time series of the entropy production rate was found to fluctuate to negative values, and moreover the probability for these events was found to be predicted accurately by the Fluctuation Theorem. This experiment the first to test this version of the Fluctuation Theorem.

References

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