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Anomalous transport of cosmic rays in MHD turbulence

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The motion of cosmic rays (energetic particles) in the MHD turbulence can be quite complex. Even in the simplest setting of the fossil slab model, in which the turbulence electromagnetic field is given as a superposition of static finite amplitude, parallel propagating MHD waves, the cosmic rays can at times be trapped by a large amplitude wave packet and stay there for a long time, or can they make almost ballistic motion without much being influenced by the turbulence field. Diffusion of the cosmic rays can thus be normal, sub-diffusive, or super-diffusive, depending on the turbulence properties (turbulence energy, spectrum, presence of intermittency, etc) and the time scale considered.

We have been taking multiple approaches to tackle this problem. In this presentation, we will be introducing some of our efforts as below.

(1) Test particle simulation: In a given finite amplitude MHD turbulence, one can compute trajectories of the cosmic rays and evaluate their diffusion properties. Figure 1 gives an example of "purely 2-d" cross-field diffusion, in which all the magnetic field lines are assumed to be parallel everywhere (so that the cross-field diffusion due to "braided" field lines is artificially suppressed) [1,2]. The top panel shows some typical time series of the cosmic rays. Apparently, it is distinct from usual Brownian motion, in that it includes many segments of "halts", corresponding to the particle being trapped by magnetic islands. The bottom panel is the diffusion coefficient plotted versus time scale. As expected, the diffusion is sub-diffusive for a certain range of the time-scale. At larger time scales, the diffusion can be regarded normal.

(2) Walk-stick model: Weeks et al [3] proposed a simple model to generate a random walk sequence that can exhibit both sub- and super-diffusive characters by letting the random walker alternate between flights (steps of constant velocity) and sticking (pauses between flights). Flight and sticking time probability distribution functions are specified by a Levy distribution with different indices. The cosmic ray trajectories generated by this walk-stick model are applied to the diffusive shock acceleration process [4].

(3) A natural formalism to model ensemble of particles that undergo anomalous transport processes is the fractional diffusion equation, in which the time and/or spatial derivative involves fractional differentiation operators [5]. First, we briefly introduce the concept of the fractional differentiation/integration operators and explain how to evaluate them numerically. Then, as an important application of this model, we discuss the diffusive shock acceleration process by solving numerically the fractional convection diffusion equation. The results will be compared with those obtained by test particle simulations using sub- and super-diffusive particles. Possible applications of the present model to other high-energy astrophysical phenomena will be discussed as well.

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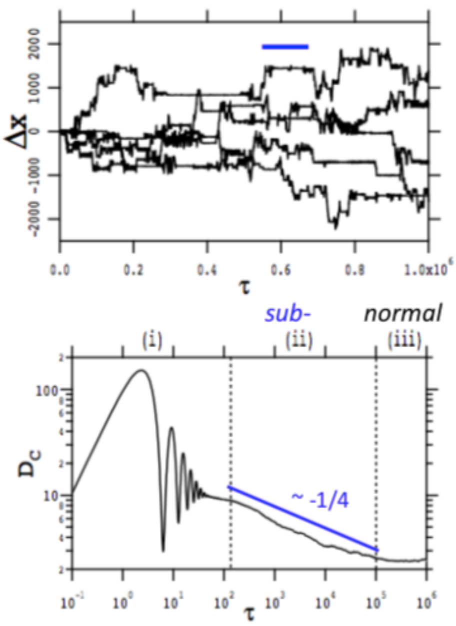

Figure 1. Trajectories and time dependent diffusion coefficient in purely 2-d cross diffusion model [2].