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Nonlinear Processes in Turbulent Astrophysical Plasmas Involving Magnetic Reconnection

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Astrophysical plasmas are usually collisionless but turbulent. As such their dynamics is controlled by non-linear interactions between particles (ions and electrons) and the turbulent electromagnetic fields collectively generated by the moving charged particles, causing alternating electric currents.

We consider as an example the turbulence of the plasma of the solar wind, propagating and interacting with obstacles like the Earth's magnetosphere. It has been known for a long time, that the propagation of the Solar wind can be understood only by considering additional heating along its path and the turbulence was identified as the way to dissipate energy into the plasma.

In fact, the observed spectra of turbulence indicate a process of cascading the magnetic and kinetic energy stored at the largest scales to smaller and smaller scales until, finally, dissipation takes place at characteristic particle scales. Since the solar wind plasma is collisionless, the dissipation must take place due to mechanisms alternative to particle collisions as their interaction with the ubiquitous turbulent electromagnetic field.

Over many years spacecraft have successfully *in-situ* investigated the solar wind turbulence at magneto-hydrodynamics scales. Observations revealed an extended inertial range of the turbulence with spectral indices α from $-5/3$ to $-3/2$. This means that energy is transferred from larger to smaller scales in a self-similar way by non-linear interactions. Only very recently, however, multi- spacecraft s/c mission like CLUSTER and MMS, finally, allowed to directly investigate the turbulence at scales at which dissipation takes place. They discovered a number of spectral breaks beyond the edge of the inertial range, at which the spectral indices change to $\alpha \sim [-4, -2]$. The actual value α depends on the plasma parameters like the ion plasma beta and the power of the excited turbulence.

With those observations it became possible to look for the nonlinear wave-particle interactions which terminate the inertial range of the collisionless astrophysical plasma turbulence by dissipation.

At a first glance, the observed kinetic-scale fluctuations seem to resemble either kinetic Alfvén waves or whistler waves. The nonlinear mechanisms of energy dissipation, which terminate the turbulence cascade and heat the particles would, therefore, be either resonant Landau or cyclotron damping or non-resonant, stochastic. Numerical studies have shown, however, that at sub-ion scales features in the frequency-space exist that cannot be explained by the observed waves but rather by coherent structures in the turbulence. The formation structures like vortices, discontinuities or thin current sheets (CSs) and their dissipation would, in fact, influence the nonlinear interactions terminating the turbulent energy cascade. This would include energy dissipation and heating by magnetic reconnection through the formed CSs. Reconnection is known as a process which causes ion outflows ("jets"). MMS observations in the shocked solar wind at the Earth, its magnetosheath, found, however, peculiar magnetic reconnection events which produce electron jets with no ion counterpart. These events were observed at thin electron-scale CSs embedded in strong turbulent fluctuations with correlation lengths of the order of just a few ion inertial lengths. Hence, the CSs formed and reconnected at scales at which the ions were decoupled from the magnetic field, i.e. electron-only reconnection took place. It, therefore, appeared that turbulence and reconnection seem to be closely linked to each other in the collisionless dissipation with the electrons playing a major role in it.

These processes can be studied best by fully kinetic simulations retaining both ion and electron kinetic effects. Hybrid simulations which consider the electrons as an inertial fluid reveal, however, already a number of nonlinear processes which take place while CSs form and thin down.

We review the current results of the investigation of the nonlinear processes in a collisionless turbulent plasma involving reconnection at kinetic scales. The Ansatz of such simulations is the initialization of a decaying turbulence by randomly-phased Alfvén-waves at large injection scales. Already hybrid simulations with inertial electron fluids reveal the formation of CSs at the smallest scales of the turbulence. These CSs continuously thin down until the electron flows become the dominating current carriers. The enhanced electron flows, finally, cause streaming instabilities and the consequent wave-particle interactions dissipate part of the available free energy of the CSs. As the thinning continues the shear flow of the particles at the edges of the CSs leads to an unstable growth of additional waves which enhances the dissipation via nonlinear wave-particle interactions. Finally, as fully kinetic simulations have currently shown, resonant effects further enhance the dissipation by triggering three-dimensional reconnection at electron scales.