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Spectral anisotropy in magnetohydrodynamic turbulence

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Abstract

In many astrophysical and laboratory plasmas, magnetohydrodynamic turbulence does not develop in a homogeneous system, on the contrary the presence of a background magnetic field has strong effects on the dynamics of such systems and on the properties of the turbulence, which develops spectral anisotropy from isotropic initial conditions. Spectral anisotropy has been observed by many spacecraft in the solar wind turbulence and in various regions of the Earth's magnetosphere, like the magnetotail and the magnetopause. There is also direct evidence of spectral anisotropy in solar wind magnetic field observations. Experiments have also suggested the existence of spectral anisotropy in laboratory plasma devices.

The distribution of energy in wavevector space is different in the directions parallel and perpendicular to the background magnetic field and the spectral index may also be modified with respect to the case of homogeneous turbulence.

We study the nonlinear evolution of three-dimensional reconnection instabilities in a configuration where a guide field is present and many resonant surfaces are simultaneously present in different locations of the simulation domain. We follow the development of the energy spectrum until the energy is transported to the dissipative length scale and we analyse the anisotropy of the spectrum. In the simulation the equilibrium magnetic field is not dissipated. This situation is similar to what can be found in astrophysical systems, like the Earth's magnetotail, where a current sheet with a guide field is present. The effect of the mean magnetic field is to produce anisotropic spectra. This effect has been investigated in the case of a uniform magnetic field in two-dimensional and three-dimensional periodic configurations. These studies have shown the development of strong anisotropies in the spectrum of the fluctuations indicating that nonlinear couplings are stronger for wave vectors perpendicular to the mean field and

greater anisotropy is found at smaller scales. In this work, we analyze anisotropy properties produced in a more realistic configuration with a sheared magnetic field. In the magnetotail and magnetopause turbulence, where the average magnetic field is not uniform, anisotropic energy spectra have been observed with spectral indexes up to $\beta = 3$. We solve numerically the incompressible, dissipative, magnetohydrodynamics (MHD) equations in dimensionless form, in a three-dimensional Cartesian domain.

Numerical results show that, at the end of the simulation the spectrum is anisotropic and it is developed mainly in the $\hat{z}$ direction, with an anisotropy angle of about 80°. The small-scale turbulence can be considered as formed by Alfvèn waves, with nonlinear interactions occurring only between modes travelling in opposite directions. Waves with wave vectors k perpendicular to B_0 have nonlinear interactions much more efficient than waves with wave vectors parallel to B_0 and they are transferred along the spectrum much faster. In our case the equilibrium magnetic field is not uniform, as in previous works, but its direction changes at different positions in the $\hat{x}$ direction. This means that the direction of development of the spectrum depends on x, being perpendicular to the local mean magnetic field. Finally, we present a comparison between our results and the magnetic field spectra observed in space plasmas.