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A NEW TURBULENCE REGIME IN THE SOLAR-WIND AT ELECTRON SCALES

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Abstract. Solar wind turbulence is characterized by a Kolmogorovian magnetic fluctuations spectrum at large scales followed by a second inertial range with steeper spectra associated with nonlinear dispersive processes. Recent observations reveal the presence of a third region – called dissipation range – at scales smaller than the electron inertial length and characterized by steeper spectra. We investigate this regime in the electron magnetohydrodynamics approximation and discuss the possibility to derive an exact and universal law for third-order structure functions. This law corresponds to a magnetic fluctuations isotropic spectrum in $k^{-11/3}$ compatible with the observations. We conclude on the possible existence of a third turbulence regime in the solar wind instead of a dissipation range as recently postulated.

Keywords: electron magnetohydrodynamics, solar wind, turbulence

1 Solar wind turbulence

Solar wind turbulence provides an ideal laboratory for studying high Reynolds number plasma turbulence. This unique situation allows us to investigate for example the origin of anisotropy, to evaluate the mean energy dissipation rate, to detect multiscale intermittency, or to analyze different regimes of turbulence characterized by a steepening of the magnetic field fluctuations spectrum with a power law index going from $-5/3$, at frequencies lower than 1Hz, to indices lying around -2.5 at higher frequencies (see *e.g.* Klein et al. 1993; Smith et al. 2006; Alexakis et al. 2007; Bigot et al. 2008; MacBride et al. 2008; Kiyani et al. 2009).

The spectral break near 1Hz has been a subject for intensive studies and controversies in the last decades. It was first interpreted as the onset of dissipation caused for example by kinetic Alfvén wave damping (Leamon et al. 1998). Then, it was demonstrated that the wave damping rate usually increases very strongly with wavenumbers and should lead to a strong cutoff in the power spectra rather than a steepened power law (Li et al. 2001). In the meantime, there are some indications that the fluctuations are accompanied by a bias of the polarization suggesting the presence of right-hand polarized, outward propagating waves (Goldstein et al. 1994). Also it was proposed (Stawicki et al. 2001) that Alfvén – left circularly polarized – fluctuations are suppressed by proton cyclotron damping and that the high frequency power law spectra are likely to consist of whistler fluctuations (Matthaeus et al. 2008). It is currently believed that the steepening of the spectra at 1Hz is mainly due to non-linear dispersive processes that range from kinetic Alfvén waves (Howes et al. 2008), electromagnetic ion-cyclotron Alfvén waves (Gary et al 2008), or/and electron whistler waves (Ghosh et al. 1996; Galtier 2006; Galtier & Buchlin 2007) in the framework of Hall magnetohydrodynamics (MHD) or simply electron MHD.

The most recent solar wind observations made with the high resolution magnetic field data of the Cluster spacecraft (Alexandrova et al. 2009; Sahraoui et al. 2009) reveal the presence of a third region – called dissipation range – at scales smaller than d_e and characterized by even steeper magnetic fluctuations spectra with a power law index around -3.8. These spectra observed only on half a decade are interpreted as either a power law (Sahraoui et al. 2009) or an exponential law (Alexandrova et al. 2009). Although the theoretical interpretation of such a regime is still open (Matthaeus et al. 2008), a recent theoretical analysis shows that a kinetic Alfvén wave cascade subject to collisionless damping cannot reach electron scales in the solar wind at 1 AU (Podesta et al. 2010). The direct consequence is that the spectra observed must be supported by another type of wave modes. It is noteworthy that this new regime at electron scales gives rise to the same controversy as the steepening found two decades ago around 1Hz which brings up naturally the following question: Have we really found the dissipation scale of the solar wind plasma or is it the onset of a new turbulence regime?

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2 Universal laws at electron scales $\ell < d_e$

The turbulence regime at scales smaller than the electron inertial length d_e has been recently investigated through the electron MHD approximation (Meyrand & Galtier 2010). The assumptions of homogeneity and isotropy are made to derive an exact and universal law for third-order structure functions. This law takes the form

$$d_i d_e^2 \langle \delta J_L (\delta \mathbf{J})^2 \rangle = \frac{4}{3} \varepsilon^J r \,, \tag{2.1}$$

with d_i the ion inertial length, $\mathbf{J}$ the current density, $\delta\mathbf{J} \equiv \mathbf{J}(\mathbf{x}+\mathbf{r}) - \mathbf{J}(\mathbf{x})$ and ε^J the mean energy dissipation rate per unit mass. By definition L means the longitudinal component of the vector, *i.e.* the one along the direction $\mathbf{r}$. The derivation of this universal law is not straightforward but then one can predict easily the form of the associated magnetic spectrum since one has the relation $\mathbf{J} = \nabla \times \mathbf{B}$; it reads

$$B^2(k) \sim \left(\frac{\varepsilon^J}{d_i d_e^2} \right)^{2/3} k^{-11/3} \,. \tag{2.2}$$

We see that the power law is compatible with the most recent solar wind measurements (-3.8). Although the assumption of isotropy is in apparent contradiction with the observations, it is claimed that the method used is a powerful way to have a first estimate of the anisotropic spectrum. Indeed, the main source of anisotropy is the presence of a large scale magnetic field which reduces the nonlinear transfer along its direction. Then, the most relevant spectral scaling is the transverse one for which the spectral index corresponds to the isotropic case if arguments based on the critical balance condition are used.

3 Conclusion

The turbulence regime at scales smaller than the electron inertial length d_e is discussed through the approximation of electron MHD. A new universal and exact law in terms of structure functions for the current density may be derived (Meyrand & Galtier 2010). This law leads to the prediction of a $k^{-11/3}$ power law spectrum for the magnetic field fluctuations compatible with the most recent observations made with Cluster. This result is the first prediction for the magnetic fluctuations spectrum at these length scales. The possibility to get a turbulence regime at electron scales questions the origin of dissipation in the solar wind and more generally in space plasmas.

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