Kinetic turbulence and ion heating in the solar wind

S. S. Cerri[1], L. Arzamasskiy[1], M. W. Kunz[1,2], B. D. G. Chandran[3]
[1] Department of Astrophysical Sciences, Princeton University, USA [2] Princeton Plasma Physics Laboratory, Princeton, USA, [1] Department of Physics, University of New Hampshire, USA
e-mail (speaker): scerri@astro.princeton.edu

A wide range of space and astrophysical environments are permeated by turbulent, hot, magnetised plasmas. Understanding the properties of turbulent fluctuations and the mechanisms underlying their turbulent cascade in such collision-less plasmas is fundamental to understand the evolution of these systems and of their large-scale emission features (e.g., [1–3]). To this end, it is crucial to determine what is the nature of the cascading fluctuations, which fundamental mechanisms are responsible for the transfer of fluctuations' energy from the large ('injection') scales of the system down to the small ('dissipation') scales, and what are the relevant processes that eventually convert the cascading energy into heat and non-thermal particles at the plasma micro-scales. However, distant astrophysical environments are clearly not accessible to direct (*in situ*) measurements. Therefore, the near-Earth environment and the solar wind provide a unique opportunity to investigate weakly collisional, magnetised plasma turbulence in great detail via accurate *in-situ* measurements of turbulent fluctuations and of particles' distribution function[4–6]. Over the past decades, space missions have indeed uncovered a complex scenario whereby several kinetic plasma processes may be simultaneously at play along the turbulent cascade. For instance, a long-lasting debate in solar-wind turbulence concerns the nature of the fluctuations at sub-ion scales, as well as the mechanisms responsible for the heating of ions. In fact, while it now seems a well-established result that at the 'large' magneto-hydrodynamic (MHD) scales — in the so-called MHD inertial range — there is an anisotropic cascade of Alfvénic fluctuations, as soon as the plasma micro-scales are approached by the cascade, kinetic processes come into play and several type of (dispersive) modes (e.g., kinetic-Alfvén and whistler waves) become available to the system[7]. Simultaneously, depending on the nature of the fluctuations, a wide range different ion-heating mechanisms (e.g., Landau damping, ion-cyclotron resonances, and stochastic heating) may remove part of the turbulent energy from the underlying cascade across ion scales. This in turn determines the amount of residual energy that is cascading further down to the electron scales, which eventually heat the electrons. Therefore, understanding what happens across the ion scales and in the sub-ion range of plasma turbulence allows one to understand what the final electron-to-ion heating is going to be: this is another long-lasting debate, known as the 'turbulent-heating problem'. In this context, alongside remote observations and *in-situ* measurements, direct numerical simulations have always played a key role in providing a test ground for the existing theories and models of plasma turbulence and turbulent heating (see, e.g., [8], and references therein). In fact, the nature of turbulent fluctuations across the ion-kinetic scales and in the sub-ion range in magnetised space plasmas, as well as the associated ion-heating processes, have been extensively investigated over the past decades by means of large-size, massively parallel kinetic simulations (e.g., [8–14]).

In the present talk, recent advances in understanding sub-ion-range turbulence and turbulent heating that have been achieved with 3D kinetic simulations are discussed. After a first part focusing on the spectral properties of electromagnetic fluctuations[8,11] and on the anisotropic cascade of ion-entropy fluctuations that involves the whole six-dimensional phase space[12], special emphasis will be put on our recent understanding of ion-heating mechanisms in different plasma regimes from 3D hybrid particle-in-cell (PIC) simulations of continuously driven Alfvénic turbulence[14,15].

References

[1] Kunz et al., *Mon. Not. Royal Astron. Soc.* **410**, 2446 (2011)
[2] Yuan & Narayan, *Annu. Rev. Astron. Astrophys.* **52**, 529 (2014)
[3] Chael et al., *Mon. Not. Royal Astron. Soc.* **478**, 5209 (2018)
[4] Bruno & Carbone, *Living Rev. Sol. Phys.* **10**, 2 (2013)
[5] Chen, *J. Plasma Phys.* **82**, 535820602 (2016)
[6] Sahraoui et al., *Rev. Mod. Plasma Phys.* **4**, 4 (2020)
[7] Schekochihin et al., *Astrophys. J. Suppl. S.* **182**, 310 (2009)
[8] Cerri et al., *Front. Astron. Space Sci.* **6**, 64 (2019)
[9] Cerri et al., *Astrophys. J. Lett.* **846**, L18 (2016)
[10] Groselj et al., *Astrophys. J.* **847**, 28 (2017)
[11] Cerri et al., *Astrophys. J. Lett.* **846**, L18 (2017)
[12] Cerri et al., *Astrophys. J. Lett.* **856**, L13 (2018)
[13] Kawazura et al., *Proc.Natl.Acad.Sci.* **116**, 771 (2019)
[14] Arzamasskiy et al., *Astrophys. J.* **879**, 53 (2019)
[15] Cerri et al., *Astrophys. J.* (to be submitted)